CENTRAL STATIONS

CENTRAL STATIONS

BY

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FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
239 WEST 39TH STREET. NEW YORK

LONDON: HILL PUBLISHING CO., LTD.
6 & 8 BOUVERIE ST., E. C.
1917

THE MAPLE PRESS YORK PA

PREFACE

A book on central stations must necessarily relate to the generation, transmission and distribution of electrical energy. Therefore, the present volume deals with these subjects—but it has not been found expedient to classify the material into these three divisions. However, consideration of each of the eighteen different section headings will render it apparent that every section does pertain to either generation, transmission, or distribution. Throughout, the treatment is such that the gist of all which is recorded can be grasped by a reader of modest mathematical attainments. In other words, a practical man can study the book understandingly.

In the opening chapters, after certain elements which occur in all electrical-energy-distribution systems have been defined, the different factors or coefficients which are utilized frequently in central station practice are discussed rather exhaustively. Among these are load factor, demand factor, diversity factor, plant factor and the like. Their application in the design and operation of central-station systems is explained and in many instances illustrated by numerical examples. Next the typical load curves or graphs which are encountered in everyday work are considered. Then the principles of circuit design—both alternating and direct-current—are given attention; examples showing how circuits are computed in practice are worked out in detail. Following the fundamentals just recited, the elements of transmission and distribution are examined. Transmission lines, substations and lightning-protection equipment are treated.

Final chapters in the book concern electrical-energy generating stations and the equipment thereof. Thus automatic voltage regulators, switchboards and switchgear are treated. The three different types of prime movers, (1) steam, (2) internal combustion engine, and (3) hydraulic, and the adaptability of each of these three different types to certain con-

ditions, are studied. Reactors and transformers are considered briefly. Numerous illustrations, showing modern central-station practice, are given in a number of the chapters of the book in connection with the text.

Although the proofs have been read and checked very carefully by a number of persons, it is possible that there remain some undiscovered errors. Readers will confer a great favor by advising the author of any such which may be revealed. Suggestions for the enlargement or improvement of future editions of the book will be greatly appreciated.

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October, 1917.

ACKNOWLEDGMENTS

The author desires to acknowledge the assistance which has been rendered by concerns and individuals in the preparation of this book. Considerable of the material is from articles by the author, which originally appeared in some of the technical periodicals, among which are:—*Power*, *Electrical Review and Western Electrician*, *National Electrical Contractor*, and *Power Plant Engineering*. Among the concerns which coöperated with the author in supplying data and copy for illustrations are:—*The General Electric Company*, Schenectady, N. Y.; *The Westinghouse Electric and Manufacturing Company*, East Pittsburgh, Pa.; *The Fitz Water-wheel Company*, Hanover, Pa.; *The Skinner Engine Company*, Erie, Pa.; *The Ames Iron Works*, Oswego, N. Y.; *The Electric Service Supplies Company*, Chicago, Ill.; and *The Allis-Chalmers Company*, Milwaukee, Wis. Certain of the illustrations are based on those in contributions published in *Electrical World*, *Electrical Review and Western Electrician*, *Coal Age*, *Engineering News* and *Practical Engineer*. Several of the tables of demand factors and diversity factors are from the valuable book, "Central Station Distributing Systems," by Gear and Williams (D. Van Nostrand Company), who have made exhaustive studies concerning central-station-distribution characteristics.

S. C. Wagner, Superintendent of Distribution of the Electric Company of Missouri, read the galley and page proofs, called attention to a number of errors and suggested numerous improvements.

Specific acknowledgments have been made in a number of instances throughout the book. If any has been omitted, it has been through oversight and, if brought to the author's attention, will be incorporated in the next edition.

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CENTRAL STATIONS

SECTION 1

DISTRIBUTION-SYSTEM NOMENCLATURE

1. Considerable Confusion Exists as to the precise meanings of the terms which are used to designate the different components (Fig. 1) of an electrical-energy-distribution system. In the following paragraphs definitions are given for some of the terms most commonly used. These definitions are, it is believed, in line with the generally accepted meanings of the words involved. Fig. 2 shows diagrammatically the important elements of a distribution system.

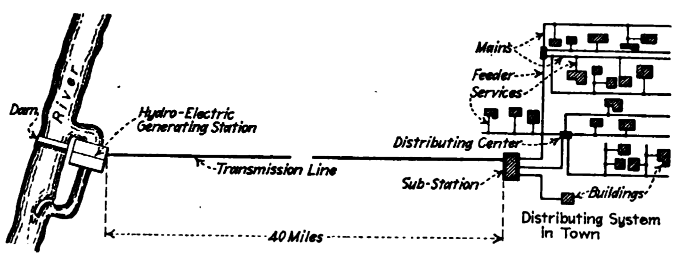


FIG. 1.—Transmission line and distributing system.

2. A Transmission Line comprises the arrangement of aerial conductors over which electrical energy is transmitted from a generating station to a sub-station. In general, the distinguishing characteristics of transmission lines are that they operate at relatively high voltages and extend for long distances. At *B* in Fig. 3 is shown the transmission line.

EXAMPLE.—A pole line between a city, industrial plant or building, and a distant generating station is a transmission line.

3. A Tie Line is a set of aerial conductors used to interconnect two sub-stations, transmission lines or any other lines.

A tie line may also operate at a high voltage and extend for a long distance but is distinguished from a transmission line in that neither of the ends of a tie line ordinarily originates in a generating station.

EXAMPLE.—A line connveying energy from one town to another in neither of which there is a generating station but both of which are supplied by some circuit other than the connecting line, is a tie line.

4. A Transmission System is one over which electrical energy is transmitted for a considerable distance from a generating station, at relatively high voltage, to a distributing system or to distributing systems. A transmission system comprises the conductors and the structures which support them.

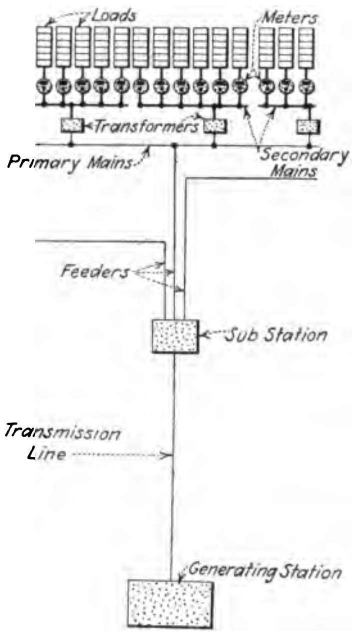


FIG. 2.—The elements of a transmission and distribution system.

5. A Distributing System is one from which electrical energy is distributed to consumers or to receiving apparatus. A distributing system consists of feeders, mains, services, etc., as shown in the illustrations. All of the wiring in a town, industrial plant or community between the sub-station (or the generating station if the energy is generated locally) and the service switches for buildings or consumers constitutes a distributing system. As a rule a distributing system operates at a lower voltage than does a transmission system.

NOTE.—It is very difficult to distinguish between a transmission and a distributing system, because:* "In any large system the functions of transmission and distribution merge into one another because the prin-

* P. H. Thomas.

cipal consumers will ordinarily be many miles apart. Furthermore, there usually are several sources of energy feeding into the system at different locations. The transmission and distribution systems then resolve themselves into a network of high-tension lines to which are connected consumers and generators at certain locations.

6. A Feeder or Feeder Circuit (Fig. 3) is the set of conductors in a distributing system extending from the original source of energy in the installation to a distributing center and having no other circuits connected to it between the source and the center. The source may be a generating or substation or a service. Feeders are indicated by the letter *D* in Fig. 3.

7. A Sub-feeder is an extension of a feeder from one distribution center to another and having no other circuit connected to it between the two distribution centers. A sub-feeder is a sort of a tie line.

8. A Main (*E* and *G*, Fig. 3) is any supply circuit to which other consuming circuits—sub-mains, branches or services—are connected through automatic cut-outs—fuses or circuit-breakers—at different points along its length. Where a main is supplied by a feeder the main is frequently of smaller wire than the feeder which serves it. An energy utilizing device is never connected directly to a main, a cut-out always being interposed between the device and the main.

9. A Sub-main (E_1, Fig. 3) is a subsidiary main fed, through a cut-out, from a main or another sub-main and to which branch circuits or services are connected through cut-outs.

10. A Service (or a service connection, *H*, Fig. 3) is the set of conductors constituting an underground or overhead connection between conductors (usually belonging to a public service corporation) in a thoroughfare—street—and the conductors of an interior or isolated wiring system. A "service" provides a path over which electrical energy is delivered to the consumers.

11. A Branch or Branch Circuit is the set of conductors, feeding through an automatic cut-out (from a distribution center, main or sub-main) to which one or more energy utilizing devices are connected directly, that is, without the interposition of additional cut-outs. The only cut-out associated with

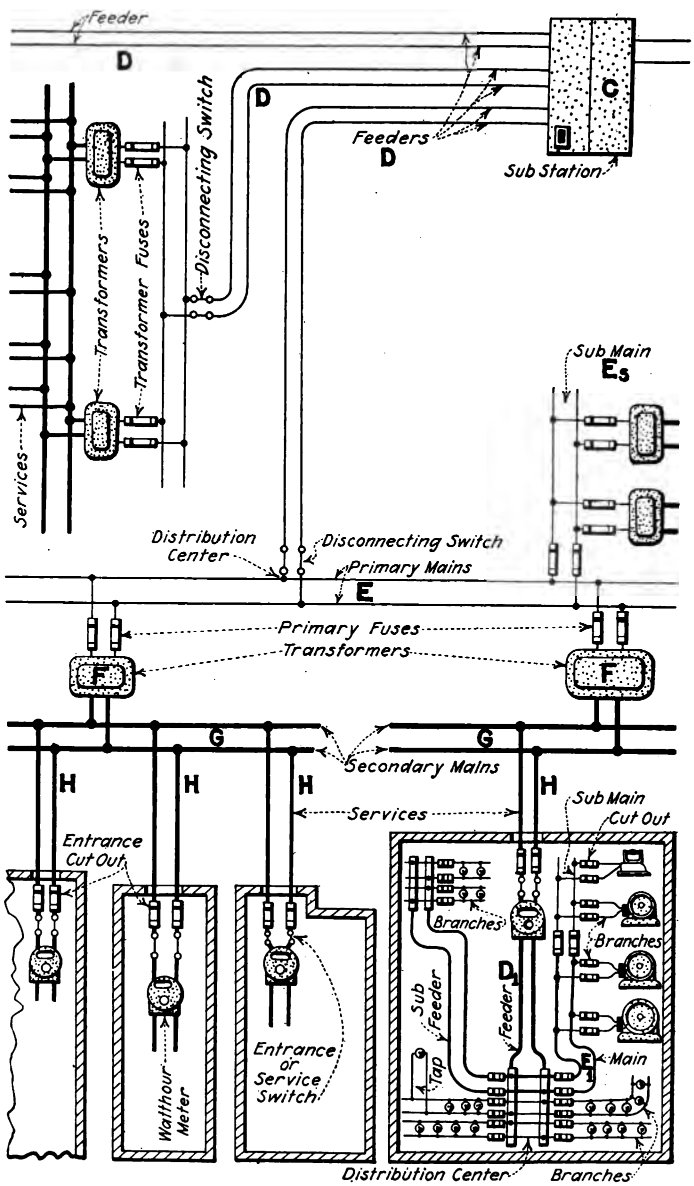
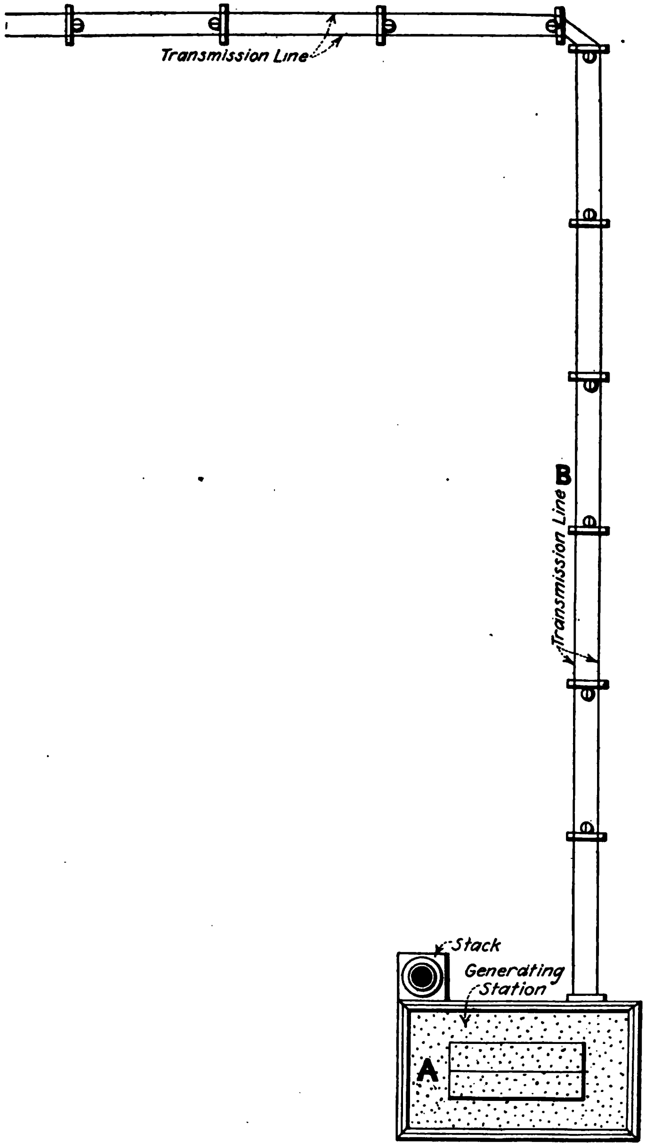


FIG. 3.—Pictorial diagram indicating the elements



of an electrical-energy distribution system.

a branch is the one through which the branch is fed at the main, sub-main or distribution center.

12. A Tap or Tap Circuit (Fig. 3) is a circuit, serving a single energy-utilizing device, connected directly to a branch without the interposition of a cut-out.

13. A Distributing or Distribution Center (Fig. 3) in an electrical energy distribution system is the location at which a feeder or sub-feeder connects to the subordinate circuits which it serves. The switches and automatic cut-outs for the control and protection of the sub-circuits are usually grouped at the distribution center. In interior-wiring parlance, a distribution center is an arrangement or group of fittings whereby two or more minor circuits are connected at a common point to another, larger circuit. A panel box is one form of a distribution center.

14. The Nomenclature of Interior-wiring-system Circuit Elements is similar to that for an outside distribution system.* The terms feeder, sub-feeder, main, sub-main, branch, tap and distribution center are defined diagrammatically in the wiring layout shown in the lower part of the center of Fig. 3. From inspection it is evident that these feeder-system elements can also be defined in essentially the same words as recited for the outside distribution-system elements recited above.

* See the author's AMERICAN ELECTRICIANS' HANDBOOK, p. 109, for detail.

SECTION 2

DISTRIBUTION LOSS AND DISTRIBUTION-LOSS FACTORS

15. Distribution Losses are those losses of electrical energy which occur in a central-station system between the station feeding the community and the receiving devices on the customers' premises. These same energy losses are sometimes referred to as "*energy lost or unaccounted for*" or "*kilowatt-hours lost or unaccounted for.*" In every electrical-energy-distribution plant, the total kilowatt-hours delivered to the distribution-system lines, as recorded by the station totalizing watt-hour meter, during a given interval of time will always be greater than the sum of the kilowatt-hours registered on all of the consumers' meters or similarly accounted for during the same interval of time. The difference between the energy thus delivered to the distributing system and that accounted for, represents energy-distribution losses or "energy unaccounted for."

EXAMPLE.—In a certain Middle-Western town of 6,000 people the central station operates a 2,200-volt-primary, 110–220-volt, three-wire-secondary system. There are a large number of small transformers and there is considerable leakage where the primary-line wires come into contact with the limbs of trees. During the year of 1914 the plant generated and delivered to the lines 348,000 kw-hr. of energy. During the same year the energy recorded on all of the customers' watt-hour meters and otherwise accounted for was only 251,000 kw.-hr. Hence, in this instance the energy *distribution loss* was: 348,000 − 251,000 = 97,000 *kw.-hr.*

EXAMPLE.—In a town of less than 1,000 inhabitants in Iowa where a 110–220-volt alternating-current, three-wire system (without transformers) is used for distribution, the central station delivered in 1913 to the lines 25,000 kw.-hr. The customers' meters, for the same interval, recorded 23,000 kw.-hr. Hence, for this plant and this year, the distribution loss was: 25,000 − 23,000 = 2,000 *kw.-hr.*

EXAMPLE.—For the year ending June 30, 1915* The Pacific Power and Light Company, which operates in the States of Oregon and southern Washington, generated or bought 45,473,923 kw.-hr. of energy. For the same period, the energy delivered to customers or otherwise accounted for was only 37,746,854 kw.-hr. Hence, the distribution loss for that year was 7,727,069 kw.-hr.

16. Distribution Loss Includes all of the energy which is not delivered to customers or otherwise accounted for and is made up of, or comprises, a number of secondary losses which may be enumerated thus:

(a) *Line loss* ($I^2 \times R$ *losses) in the line conductors, feeders, mains and services.*

(b) *Leakage loss (due to insufficient insulation, grounds against trees and the like).*

(c) *Transformer loss (due to the iron and copper losses in the transformers. These occur only in alternating-current plants).*

(d) *Meter loss (due to slow meters and to the electrical losses within the meters).*

(e) *Stolen-energy loss (occasioned by "theft of current").*

17. The Line Loss—that is the kilowatt-hours energy lost in the line conductors—can be readily computed if the resistance of the line and the current in it is known, because: *Watts line loss* = (*line current in amp.*)^2 × (*resistance of line in ohms*). Then, if the watts power loss thus obtained be multiplied by the number of hours during which the current flows, the kilowatt-hour energy line loss will be the result. Since the current in a distribution line is seldom constant, it is necessary to recognize this condition in computing energy line loss. The line current will vary from hour to hour and month to month. However, the approximate loss can be readily calculated if 24-hr. load curves for four typical months of the year—say March, June, September and December—are available. The load factor of the plant has, obviously, a bearing on its line loss. The process is a trifle tedious and a detailed description of it would be out of place here.†

* *Electrical Review*, Nov. 13, 1915; p. 901.

† For a complete discussion of the method see Gear and Williams, ELECTRIC CENTRAL STATION DISTRIBUTING SYSTEMS, p. 274.

NOTE.—The line loss may be either a large or a small proportion of the distribution loss, depending on whether large or the smallest feasible conductors are used for the distribution lines. If the designer provides excessively large conductors, the line loss will then be very small. However, as plants are usually designed, the line loss is relatively small. The matter of the economic conductor design is treated in detail in various standard works.

18. The Leakage Loss will be determined wholly by the thoroughness with which the line was originally constructed and by the effectiveness of its maintenance. If the conductors are supported on insulators of proper design and material, if the conductors are held away from tree branches on insulators and if the trees through which the line passes are well trimmed, the leakage loss will be very small. There is no practicable method of computing the leakage losses. They *can* be determined by test, but this is usually impracticable, because it involves the simultaneous opening of every consumers' service switch.

19. Transformer Losses are subdivided into *copper losses* and *core losses*. The copper loss of each transformer varies with its load and with no load on a transformer its copper loss is very small. The iron loss is practically constant so long as normal line voltage is impressed across the primary terminals of the transformer—whether the secondary is loaded or not. The transformer loss is likely to be a large proportion of the total distribution loss, particularly where the load is almost wholly lighting and the plant operates 24 hr. a day—because the core loss is "building up" every hour that the transformer is connected to the line. Small underloaded transformers are a source of excessive loss. Hence, the capacities of transformers should be carefully determined so that, in general, a few large fully-loaded transformers will be used rather than many small underloaded ones.

NOTE.—The transformer loss of a system may be computed approximately, if the ratings of the different transformers, their efficiencies and the loads and duration thereof which are imposed on them are known. The process is tedious but feasible.

19a. Meter Losses are relatively small although they may in the aggregate be, contrary to the generally accepted opin-

ion, greater than the line losses. The power loss in the shunt or voltage coils of watt-hour meters will, probably, range between 1 watt and 4 watts. Meters of the older designs appear to have the greater losses. The power loss in the voltage coil of an average modern meter is, likely, in the neighborhood of 2.4 watts. The power loss in the current coil is very small, almost negligible, even when it does occur—and it occurs only when current to serve a load is passing through the meter. But the loss in the voltage coil occurs continuously—as long as voltage is impressed on the meter. The total aggregate energy loss thus involved may be relatively considerable as indicated by the following example.

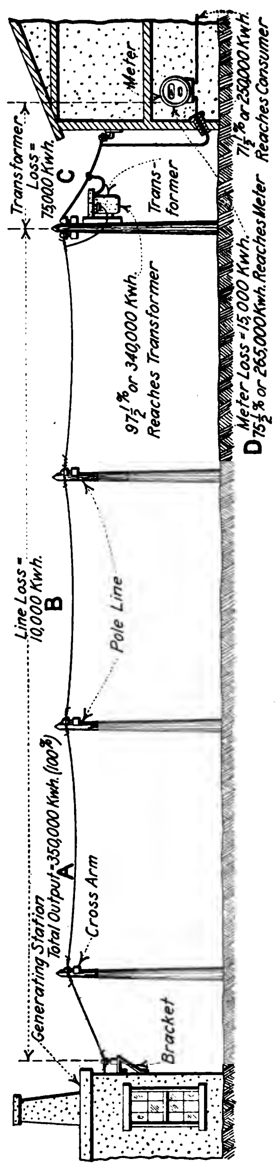


FIG. 4.—Illustrating the distribution losses in a small, alternating-current, central station system.

EXAMPLE.—If the power loss in the voltage coil of a watt-hour meter is 1.5 watts and the meter is connected to the lines of a plant giving 24-hr. service, what will be the energy loss in this coil in a year? SOLUTION.—There are 8,760 hr. in a year. Hence, the energy loss in a year would be: 1.5 *watts* × 8,760 *hr.* = 13,140 *watt-hr.* = 13.1 *kw.-hr.*

20. Stolen-energy Loss is, obviously, difficult of determination. Whether or not it assumes material values depends largely on the policy and vigilance of the concern which is giving service. However, in any case, it is likely to be but a small proportion of the total distribution loss, but it is, probably, larger than most people imagine.

21. A Specific Numerical Illustration of Distribution Loss and the Segregation Thereof is given graphically in Fig. 4. The values there shown, and also recited in Table 22, were computed from actual operating data, for the year 1913, of a central-station plant in a city of about 6,500 inhabitants in Missouri. The 60-cycle, two-phase, distribution system under consideration comprises 2,400 volts primary and a 110–220-volts, three-wire secondary. While the distribution loss indicated in Fig. 4 is greater than it would be in a well-designed distribution plant, there are, probably, many small central-station systems operating in the United States which could not show a much better performance.

EXPLANATION.—During the year 1913, 250,000 kw.-hr. of electrical energy were delivered to the customers of this central station. During this same interval, there were supplied to the distribution system 350,000 kw.-hr. Hence, the distribution loss was: 350,000 − 250,000 *kw.-hr.* = 100,000 *kw.-hr.*, during this year. It was estimated, on the basis of careful calculations, that the annual line transformer, and meter losses were about as shown in Table 22. No specific estimates of leakage loss or stolen energy were made, it being, probably, assumed that these were included in the three loss items which were estimated.

The distribution plant included 60 transformers ranging in capacity from 2 kva. to 40 kva. all but four being under 20 kva. in capacity. Probably many of these transformers were of old inefficient types. There were 973 watt-hour meters in the installation ranging in capacity from 200 amp. to 5 amp.; all but 11 were of 50 amp. or less capacity. There were 704 5-amp. watt-hour meters.

A consideration of these data (Fig. 4 and Table 22) will emphasize the importance of using only high-efficiency transformers, if the distribution loss is to be maintained at a minimum, because in this example the transformer loss was much the greatest of any of the distribution losses. The meter loss was greater by 5,000 kw.-hr. than the line loss. These data show that the usually accepted notion that the line loss is always the greatest of the distribution losses may not, by any means, always be right.

These data indicate the conditions obtaining in the small-city distribution plant discussed in more detail in the preceding explanation.

22. Example of Losses in the Distribution of Electrical Energy

Item	Annual kilowatt-hours	In per cent. of energy gen.	In per cent. of energy deliv.
Line loss	10,000	2.9	4.0
Transformer loss	75,000	21.3	30.0
Meter loss	15,000	4.3	6.0
Total distribution loss	100,000	28.5	40.0
Supplied to system	350,000	100.0	140.0
Delivered to consumers and accounted for	250,000	71.5	100.0

23. A Distribution-loss Factor is that value, relating to some particular system, expressed as a percentage, which, if the *energy delivered and accounted for* be multiplied by it, will give the *energy lost in distribution.* It is the per cent. of energy "sold" which is lost and unaccounted for in distribution. Therefore:

$$(1)\quad \textit{Distribution-loss factor} = \frac{\textit{kw.-hr. distribution loss}}{\textit{kw.-hr. delivered and accounted for}}$$

(2) Hence, *kw.-hr. dist. loss* = (*dist.-loss factor*) × (*kw.-hr. del. and acc. for*).

and

$$(3)\qquad \textit{kw.-hr. del. and acc. for} = \frac{\textit{kw.-hr. dist. loss}}{\textit{dist.-loss factor}}$$

NOTE that the kilowatt-hours delivered and the kilowatt-hours lost must both be measured over the same interval of time—preferably over an extended interval such as 6 months or a year.

EXAMPLE.—In the case of the Missouri small-city system (Art. 21) the energy supplied to the system in the year of 1913 was 350,000 kw.-hr. During the same year, the energy delivered to consumers was 250,000 kw.-hr. What was the distribution-loss factor for this plant for the year 1913? SOLUTION.—The distribution loss was: 350,000 − 250,000 = 100,000 *kw.-hr.* Now substitute in equation (1): *Dist.-loss factor* = (*kw.-hr. dist. loss*) ÷ (*kw.-hr. del. and acc. for*) = 100,000 ÷ 250,000 = 0.40 = 40 *per cent.* Hence, the distribution-loss factor for this plant for this year was 40 per cent.

EXAMPLE.—In a certain small town of 500 inhabitants it was estimated that the total energy sold would be 16,370 kw.-hr. annually. If it be

decided that the town will be served by an alternating-current 2,400-volts-primary 110-volts-secondary system and that a loss factor of 20 per cent. be assumed, how many kilowatt-hour will have to be generated annually? SOLUTION.—From equation (2): *kw.-hr. dist.-loss* = (*dist.-loss factor*) × (*kw.-hr. del. and acc. for*) = 0.20 × 16,370 = 3,274 *kw.-hr.* That is, the annual distribution loss would be 3,274 kw.-hr. Then, there would have to be generated: 16,370 + 3,274 = 19,644 *kw.-hr.* Or, a more direct solution is: 16,370 × 1.20 = 19,644 *kw.-hr.*

EXAMPLE.—In a certain central-station plant there are 789,600 kw.-hr. supplied to the distribution system annually. If the distribution-loss factor for this system is assumed to be 25 per cent., how much energy is delivered to customers and otherwise accounted for annually? SOLUTION. —From the preceding discussion it follows that, equation (3): *Kw.-hr. del. and acc. for* = (*kw.-hr. supplied to dist. system*) ÷ (100 + *dist.-loss factor*) = 789,600 ÷ 1.25 = 631,000 *kw.-hr.* Hence, 631,000 kw.-hr. of energy would annually be delivered to the customers of this system.

24. Probable Distribution-loss Factors, that is, factors that will, probably, apply for certain different conditions of service are given in Table 26. These are based on data from a number of cases encountered in actual practice and are believed to be representative. The "probable-fair-average-value" values may be used in making estimates. It should be understood, as hereinbefore suggested, that the distribution-loss factor for any certain installation will be determined wholly by the characteristics of that system.

NOTE.—For a central station where a residence-lighting load predominates and there is little power load, the distribution-loss factor will be much higher than where the power load is predominant. The reason for this is that with the residence-lighting load, the transformer loss will be proportionally large. It is also true that distribution losses will usually be greater, relatively, for a residence district where the consumers are widely scattered than for a district where the loading is dense, for the reason that a few large well-loaded efficient transformers can be used for serving the dense load while the scattered load will, probably, be fed by many small underloaded less-efficient transformers.

25. Line-loss Factor.—A line-loss factor is a value representing the ratio of the actual $I^2 \times R$ energy loss in a feeder or other line circuit component during a year to the $I^2 \times R$ energy loss that would have occurred in that feeder—or other circuit component—if it had carried continuously the maxi-

mum load ever imposed on it during the entire year. This factor is sometimes indefinitely referred to as merely "loss factor." It is somewhat similar in derivation to load factor, which is the ratio of the average load imposed on a station or system to the maximum load imposed on it. Ordinarily, it is impossible to obtain the "actual" $I^2 \times R$ energy loss in a circuit, hence in computing line-loss factor in practice, an estimated approximate value is determined in accordance with the process referred to in a preceding paragraph.

26. Approximate Distribution-loss Factors.—Values based on data from actual practice. These values contemplate all of the losses tabulated in Art. 16.

	Kind of plant and general conditions	Distribution-loss factors	
		Probable range	Probable fair average value
Alternating current	Without transformers and well-designed; 110–220 three-wire or 440-volt.	10–220	15
Alternating current	Well-designed system 2,200, 2,400 or 6,600-volt primary and 220 or 440-volt secondary; largely power load of reasonably high load factor.	15–25	20
Alternating current	Well-designed system; 2,200 or 2,400-volt primary and 110–200-volt three-wire secondary; general lighting and power load.	20–30	25
Alternating current	Poorly-designed system; large number of small transformers; 2,200 or 2,400-volt primary and 110–220-volt secondary; general lighting and power load.	25–45	35
Direct current	Well-designed; lighting and power load	5–20	10
Direct current	Poorly designed; lighting and power load.	10–25	15

SECTION 3

MAXIMUM DEMAND AND DEMAND FACTORS

27. The Demand of an Installation or System* is "the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes or other suitable units." It should be noted that "the load is averaged over an interval of time." Hence, it follows from this definition that there is no such thing as an "instantaneous demand." In other words, the demand of an installation is the requirement—usually power requirement—of that installation averaged over a time interval.

28. The Average Demand of an installation is the average requirement—usually power requirement—of the installation during some specified interval of time of considerable duration such as a day, month or year. Hence, the average power demand of an installation in kilowatts for a specified interval may be obtained by dividing the kilowatt-hour energy consumed by the installation during that interval by the number of hours in the interval. This method gives an arithmetical average. That is:

$$(4)\quad kw.\ average\ demand = \frac{kw.\text{-}hr.\ during\ interval}{hours\ in\ interval} \qquad \text{(kilowatts)}$$

$$(5)\quad Hours\ in\ interval = \frac{kw\text{-}hr.\ consumed\ during\ interval}{kw.\ average\ demand} \qquad \text{(hours)}$$

(6) $Kw.\text{-}hr.\ consumed\ during\ interval = (kw.\text{-}hr.\ average\ demand) \times (hr.\ in\ interval).$ (kilowatts)

Example.—If the totalizing watthour meter of a central station indicates that the energy supplied by the station to the system is 64,723 kw.-hr. during a certain 24-hr. day what was the average power demand in kilowatt for that day? **Solution.**—From (4): *kw. average demand*

* A. I. E. E. Standardization Rules, June 28, 1916, Sec. 57.

= (*kw.-hr. consumed during interval*) ÷ (*hours in interval*) = 64,723 ÷ 24 = 2,690 *kw.*

29. The Maximum Demand of an Installation or System is* "the greatest of all the demands which have occurred during a given period. It is determined by measurement according to specifications over a prescribed time interval." By combining the definitions of "*demand*" and "*maximum demand*" above given, it is evident that the maximum demand of an installation is the greatest power load occurring during a certain relatively long period—such as a day, month or year. However, it is not the greatest *instantaneous* load

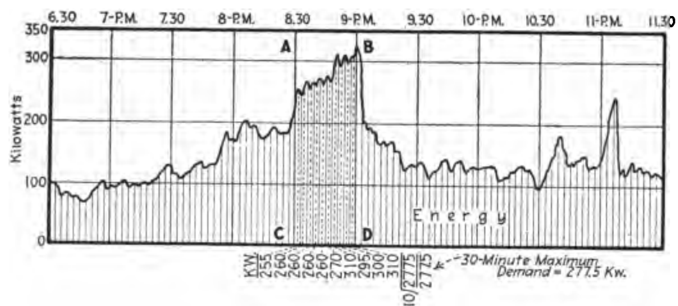


FIG. 5.—Illustrating one method of obtaining an averaged or integrated maximum demand over a 30-minute interval.

during that period but it is the greatest average power load occurring during any of the relatively short intervals of the specified or selected duration—such as 1 min., 15 min. or 30 min.—within the period. The study of the following example (Fig. 5) will assist one in obtaining an understanding of this statement. Note that, as will be explained later, the load during the specified interval is not necessarily averaged arithmetically because processes of averaging other than the arithmetical are being used.

EXAMPLE.—Fig. 5 shows the graph of a load extending over a 5-hr. period. The maximum demand of this load on a 30-min.-interval basis, is, as shown, 277.5 kw. By inspection it is apparent that the load is greater during the 30-min. interval *AB* between 8:30 and 9:00

* A. I. E. E. STANDARDIZATION RULES, June 28, 1916, Sec. 58.

P.M. than it is during any other 30-min. interval in the 5-hr. period. Then this interval, *AB,* is the one over which the demand must be averaged to ascertain the 30-min. *maximum demand* for the load suggested.

By scaling the kilowatt "instantaneous" demand at ten equidistant points between the 8:30 P.M. ordinate, *AC,* and the 9:00 P.M. ordinate *BD,* ten values of the kilowatt demands at these instants are obtained. The arithmetical average of these ten values is, as shown, 277.5 kw. Hence the 30-min. maximum, demand (averaged arihtmetically) of the load graphed in Fig. 5, is 277.5 kw.

It should be understood that the method of the above example of determining the arithmetical average is not absolutely accurate—but it is sufficiently so for practical purposes. The accuracy of the method depends on the number of ordinates which are averaged and on the precision with which the ordinates are scaled. In general, the greater the number of ordinates taken, the more exact will be the method. Maximum demand may also be determined from a graph by using a planimeter in much the same way that mean effective pressure of a steam-engine cylinder may be ascertained from an indicator diagram.

30. The Unqualified Term "Maximum Demand" is Indefinite; that is, a statement such as "the maximum demand was 125 kw." does not have a specific meaning. To render the statement of a maximum-demand value specific, it is necessary that there be stated: (1) The duration of the period under consideration; (2) the length of the time interval over which the maximum demand was averaged; (3) the method used in measuring or averaging the demand.

31. The Unit in Which Maximum Demand Should be Expressed will differ with the problem under consideration. Since, as above suggested, demand may be expressed in "kilowatts, kilovolt-amperes, amperes or other suitable units" it follows that maximum demand may also be expressed in such units. What unit is used in any instance should be determined by the purpose for which the maximum demand observation was made and by how it was made. Maximum-demand values are now, probably, most frequently expressed in kilowatts.

32. Demand Meters (see following illustrations) are instruments which record or indicate the maximum imposed by the circuit in which they are connected. They are arranged to automatically average (though the average is not necessarily

an arithmetical average) the power demand over the selected time interval for which they are designed or calibrated. Several different types—the principles and operation of some of which are briefly discussed in the succeeding paragraphs—are available. Where such instruments can be used the necessity of making tedious computations (for determining the maximum demand) is eliminated.

NOTE.—Since, in accordance with A. I. E. E. STANDARDIZATION RULE 58, above quoted, maximum demand may be "determined by measurement according to specifications" several different principles have, as will be shown, been utilized for maximum-demand meters. Furthermore, the different meters operating under these various principles will not necessarily indicate the same maximum-demand value when connected in a circuit serving the same load.

33. The Reason Why It Is The Average Maximum Demand Over a Certain Definite Interval That is of Interest rather than the "instantaneous maximum demand" is this: Maximum-demand determinations are made most frequently—if not always—to enable one to estimate the capacity (cost) of the electrical apparatus or equipment required to serve a certain specified load. Maximum-demand values are, it is true, important factors in the fixing of rates for electric service, but the reason that they are of importance is because of the bearing that they have in establishing the capacity of the equipment, or indirectly, the investment that will be required to serve the consumers. Now, practically all electrical apparatus will safely carry considerable—possibly 100 per cent. or greater—overloads for short periods without permanently adverse effects. Hence, it is not logical or economically desirable to so select the capacity of a device that the device will be capable of carrying continuously the kilowatt load which will be imposed on it only momentarily or for very short intervals. However, the device must, if it is not to be damaged, be capable of safely and effectively carrying the maximum load which will be imposed on it for continued periods. For these reasons "maximum demand" is defined as suggested above.

EXAMPLE.—Fig. 6 is the graph of the power load to be impressed on a certain generator, showing how the demand in this particular case varies

with the time. At *A*, *B*, *C* and *D* are load "peaks" of respectively 180, 230, 200, and 290 kw. But all of these peaks extend over relatively short intervals, possibly from 5 to 12 min. Hence, it would not—for the reasons outlined above—be logical nor necessary to select the capacity of the generator, which is to be installed to carry the load such that it could carry *continuously* the 290 kw. of the peak *D*, the 200-kw. peak of

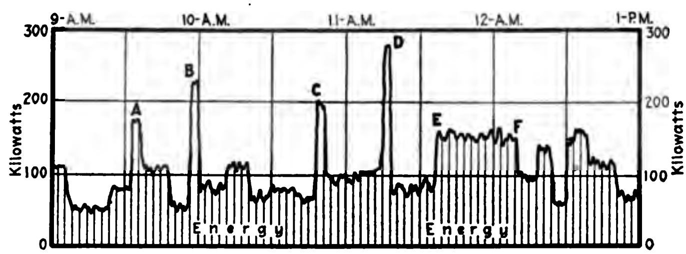


FIG. 6.—Graph showing power load to be imposed on generator.

C, the 230-kw. peak of *B* or the 180 peak of *A*. However, at *EF* is a demand of about 150 kw. which continues for something over 30 min. or a half hour. A demand extending over this period would have a very appreciable heating effect on the generator serving it. Hence, in this specific example, the consideration that should, probably, determine the

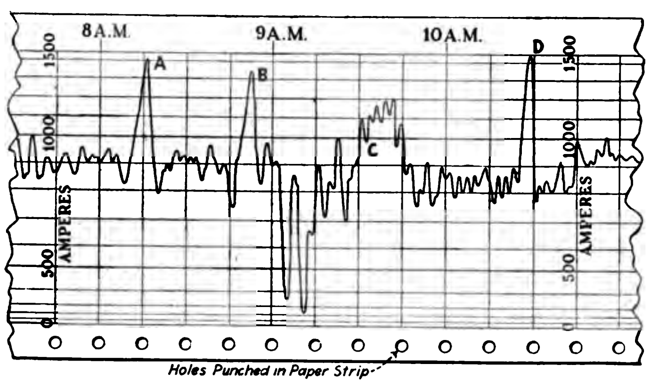


FIG. 7.—Graph of current (amperes) demand, made by a graphic ammeter.

capacity of the generator to be selected is the 30-min. maximum demand *EF*, of 150 kw.—it, of course, being assumed that the load conditions for the 4-hr. period graphed in Fig. 6 are fairly typical of the conditions which exist during *any* period of the generator's operation.

EXAMPLE.—In Fig. 7 is reproduced a (reduced) portion of a graph from a graphic ammeter. The 30-min.-ampere-maximum demand for the

load which this graph records, is, as shown at C, about 1,100 amp. The peaks at A, B and D represent very-short-interval demands which, probably would not be of great consequence in choosing the proper capacity of electrical apparatus to serve a load of the characteristics shown in Fig. 7.

EXAMPLE.—The piece of a graphic wattmeter record shown in Fig. 8 records short-period peaks at A, B and E. However, the 15-min. maximum demand of this load is about 1,000 kw. as shown at C. The 30-min. maximum demand is about 900 or 950 kw., as shown at D.

34. The Time Interval Adopted in Practice, for maximum-demand determinations, over which the greatest demand is averaged* varies somewhat with the characteristics of the load

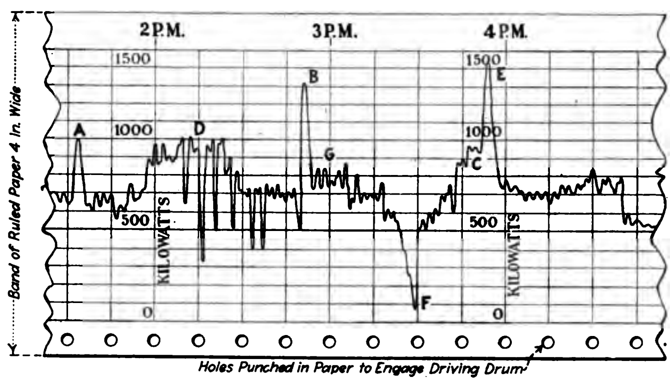


FIG. 8.—Graph of power demand made by a graphic "curve-drawing" wattmeter.

under observation and with the policy of the concern which is measuring the demand. Probably a 15-min. interval is now used more generally than any other. Hence, when a maximum demand in kilowatts or amperes is specified and no time interval is stated, the chances are that a 15-min. interval is usually implied.

NOTE.—It appears that it is the tendency of some of the State Public Service Commissions to advocate a 30-min. time interval because this interval—other things being equal—is, it is asserted, the more logical for equipment-capacity determinations than is a much longer or a much shorter one. For this reason it is possible that a 30-min. interval will, in the future, be adopted more generally. There are, likely, but very

* A. I. E. E. STANDARDIZATION RULES, No. 57.

few cases where a demand interval much longer than 30 min. should be adopted.

35. The Time Intervals for Which Maximum Demand Meters May be Adjusted are different for the instruments of

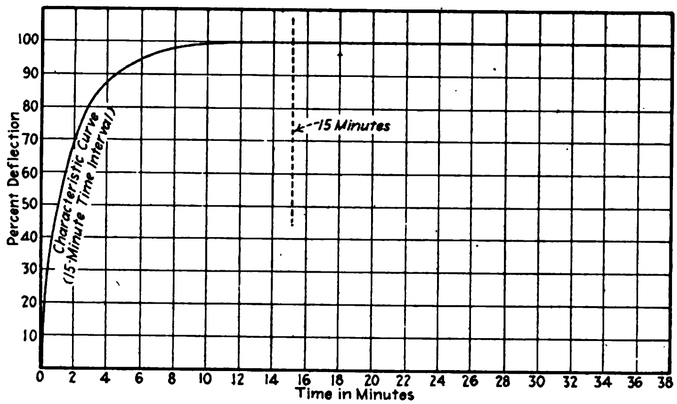


FIG. 9.—Typical characteristic curve of a lagged-type demand meter made for a 15-minute time interval.

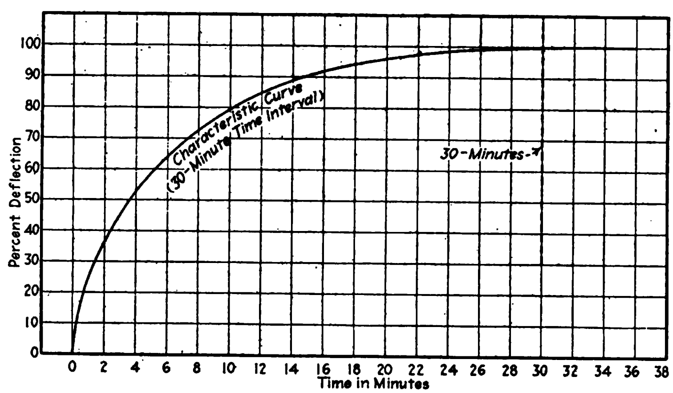


FIG. 10.—Typical characteristic curve of a lagged-type demand meter made for a 30-minute time interval.

the different types. One type of thermostatic indicator is adapted for only one interval—30 min. "Printometer" indicators (see following illustrations) can be obtained which, by providing a suitable contact-making clock, will print at the

end of every 5, 10, 15, 30 or 60-min. interval. Watt-hour-demand meters can be obtained which will indicate the average maximum demand over 1, 2, 5, 15 or 30-min. intervals. Other, induction-type, demand meters can be adjusted for only 15-min. and 30-min. intervals. In certain cases difficulty has been experienced in obtaining accurate readings over intervals much shorter than 5 min., because, apparently, the maximum-demand mechanisms are unable to operate effectively on short-interval calibrations. The "Wright" maximum-demand meter which is, apparently, being superceded by other types, has a time interval of approximately 15 min. Figs. 9 and 10 show respectively typical characteristic curves for a 15-min. and a 30-min. demand meter of the lagged type.

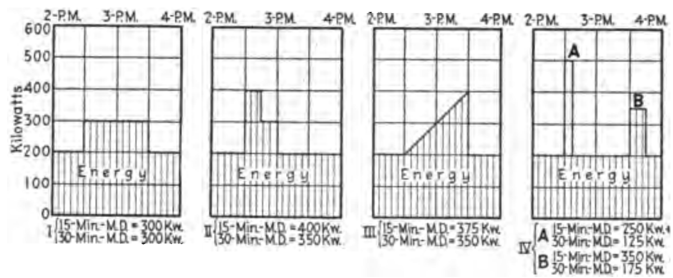


FIG. 11.—Illustrating the effect of length of time interval on maximum demand.

36. Examples Illustrating the Effect of the Length of the Time Interval on the Resultant Maximum Demand are given in the problems immediately succeeding. All of them refer to the graphs of Fig. 11. They are all imaginary cases and in them the demand is averaged arithmetically but a consideration of them will bring out the facts.

EXAMPLE I (see Fig. 11).—15-min. interval: *Kw. M.D.* = *kw.-hr.* + *H* = (300 *kw.* × 0.25 *hr.*) ÷ 0.25 *hr.* = 75 *kw-hr.* 0.25 *hr.* = 300 *kw.* = 15-*min.-interval maximum demand.*

30-min. interval: *Kw. M.D.* = *kw.-hr.* ÷ *H* = (300 *kw.* × 0.50 *hr.*) ÷ 0.50 *hr.* = 150 *kw-hr.* ÷ 0.50 *hr.* = 300 *kw.* = 30-*min.-interval maximum demand.*

EXAMPLE II.—15-min. interval: *Kw. M.D.* = *kw.-hr.* ÷ *H* = (400 *kw.* × 0.25 *hr.*) ÷ 0.25 *hr.* = 100 *kw.-hr.* ÷ 0.25 *hr.* = 400 *kw.* = 15-*min.-interval maximum demand.*

30-min. interval: *Kw. M.D.* = *kw.-hr.* ÷ *H* = [(400 *kw.* × 0.25 *hr.*) × (300 *kw.* × 0.25 *hr.*)] ÷ 0.50 *hr.* = (100 *kw.-hr.* 75 *kw.-hr.*) + 0.50 *hr.* = 175 *kw.-hr.* ÷ 0.50 *hr.* = 350 *kw.* – *30-min.-interval maximum demand.*

EXAMPLE III.—15-min. interval: *Kw. M.D.* = *kw.-hr.* ÷ *H* = [(350 *kw.* + 400 *kw.*) ÷ 2] × 0.25 *hr.* ÷ 0.25 *hr.* = 93.75 *kw.-hr.* ÷ 0.25 *hr.* = 375 *kw.* = *15-min.-interval maximum demand.*

30-min. interval: *Kw. M.D.* = *kw-hr.* ÷ *H* = [(300 *kw.* + 400 *kw.*) ÷ 2] × 0.50 *hr.* ÷ 0.50 *hr.* = 175 *kw.-hr.* ÷ 0.50 *hr.* = 350 *kw.* = *30-min.-interval maximum demand.*

EXAMPLE IV.—*A.* 15-min. interval: *Kw. M.D.* = *kw.-hr.* ÷ *H* = (500 *kw.* × 0.125 *hr.*) ÷ 0.25 × 62.5 *kw.-hr.* ÷ 0.25 *hr.* = 250 *kw.* = *15-min.-interval maximum demand.*

A. 30-min. interval: *Kw. M.D.* = *kw.-hr.* ÷ *H* = (500 *kw.* × 0.125) 0.50 *hr.* = 62.5 *kw.-hr.* ÷ 0.50 *hr.* = 125 *kw.* = *30-min.-interval maximum demand.*

EXAMPLE IV.—*B.* 15-min. interval: *Kw. M.D.* = *Kw.-hr.* ÷ *H* = (350 *kw.* × 0.25 *hr.*) ÷ 0.25 *hr.* = 87.5 *kw.* ÷ 0.25 *hr.* = 350 *kw.* = 15-min.-*interval maximum demand.*

B. 30-min. interval: *Kw. M.D.* = *Kw.-hr.* ÷ *H* = (350 *kw.* × 0.25 *hr.* ÷ 0.50 *hr.*) 87.5 *kw'-hr.* ÷ 0.50 *hr.* = 175 *kw.* = *30-min.-interval maximum demand.*

37. The Methods of Averaging the Load Over a Specified Time Interval to obtain the maximum demand may be divided into two general classes. (1) *Arithmetical average.* The maximum demand value obtained by this method is sometimes called an integrated maximum demand. (2) *Averages—so-called—other than the arithmetical.*

Where a maximum demand value is computed from the record of a graphic instrument (as for example in Fig. 5) or from a series of readings from an indicating instrument, the arithmetical average is the one ordinarily taken. Furthermore, the integrating-type demand meters provide maximum-demand values which may be averaged or which have been automatically averaged arithmetically over the time interval for which the instrument is set.

Maximum-demand values provided by certain of the so-called lagged-type demand meters are averaged by the instrument, not arithmetically, but "logarithmically or otherwise." It is unfortunate that some one method of averaging to obtain the maximum-demand values has not been standardized, be-

cause, until some specific one is, there will be confusion. As conditions now exist, when a maximum-demand value is stated it has no particular significance unless supplementary information is added. The reason why the different methods of averaging are encountered, is that the different operating principles utilized in the several types of demand meters now manufactured, inherently provide different averaging methods.

38. Demand Meters of Different Types Will not Always Give the Same Rating on the Same Load, because, as above suggested, of the principles that they involve in "averaging" the demand over the specified time interval. If a number of demand meters of the different types are all connected to the same steady load for a sufficiently long interval of time all of them will ultimately indicate the same maximum-demand value. But on fluctuating loads the demand values indicated by the instruments which operate on the different fundamental principles, some of which are briefly discussed below, may be different.

39. A Classification of Demand-measuring Instruments is shown in Table 40. While this schedule is not complete it suggests in a general way the underlying characteristics of some of the devices most frequently used in America. It is not unlikely that at some future time, because of the "survival of the fittest" law a much simpler classification will comprehend all of the demand-measuring instruments used commercially.

40. Classification of Instruments Used for Determining Maximum Demand.—This is based on the general scheme of classification originally proposed by Mr. C. I. Hall of the General Electric Company. The list of instruments tabulated under the heading "Kinds of Instruments or Indicators Available" is not intended to be complete as lines of instruments for this service may now be considered as being in the development stage.

No.	Type of instrument		Principle of operation of instrument		Kinds of instruments or indicators available (Some of the types of instruments listed are obsolete and others are practically obsolete)			
1	Indicating wattmeters or ammeters and voltmeters		Instruments may operate on any principle which affords accurate indications.	A	Any indicating wattmeter or ammeter and voltmeter.	a	A.C.	Types too numerous to enumerate.
						b	D.C.	Types too numerous to enumerate.
2	Graphic wattmeters.		Instrument may operate on any principle which provides an accurate graphic record of power consumption.	B	Any graphic wattmeter.	c	A.C.	G.E. Type Ca. G.E. Type CR. Esterline. Westinghouse Graphic. Westinghouse Type U. Bristol.
						d	D.C.	Ge Type C4. G. E. Type CR. Bristol. Westinghouse Graphic. Westinghouse Type U. Esterline.
3	Demand meters.	I Lagged	Maximum demand with pointer, pen or indicator lagged or retarded by dash pots, viscous fluids, heat, escapements, or magnets. Log or device which pushes pen, pointer or indicator forward is not returned to zero at end of each time interval.	C	Speed of pointer progression on steady load is uniform.	e	A.C.	Westinghouse Type Ro.
						f	D.C.	
				D	Speed of pointer progression on steady load varies inversely as some function of the time.	g	A.C.	G. E. Wright Demand Indicator. Thermostatic types. Heat Storage Types.
						h	D.C.	G.E. Wright Demand Indicator. Thermostatic Types. Heat Storage Types.
		II Integrating	Maximum-demand pointer, pen or register is actually pushed forward by mechanism controlled by a watt-hour meter.	E	Time intervals automatically determined by instrument.	i	A.C.	G.E. Type M4 (Indicating). G.E. Type P_2 (Printometer). G.E. Type G_2 (Graphic).
						j	D.C.	G.E. Type M_3 (Indicating). G.E. Type P_2 (Printometer). G.E. Type G_2 (Graphic).
				F	Time interval may be selected by observer.	k	A.C.	
						l	D.C.	

41. In Determining Maximum Demand With an Indicating Ammeter it is necessary to observe current-intensity values at equidistant intervals on the circuit under consideration. Then, these values may be plotted into a graph similar to that of Fig. 5, wherefrom the maximum-demand value over the selected time interval can be computed. If it is necessary that the demand value be in kilowatts it is also necessary to observe simultaneous voltage values wherefrom the power can be computed. On the commercial constant-potential circuits it is usually considered unnecessary to make simultaneous voltage readings, inasmuch as the ampere maximum demand is usually the most important for this service. Where the load is reasonably steady it is usually sufficient to take instru-

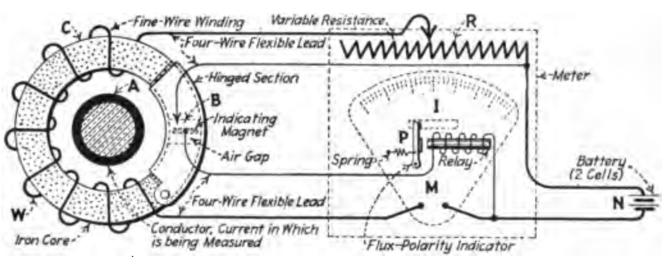


FIG. 12.—Knopp test set for determining current in direct-current conductors.

ment readings every 5 min. But with fluctuating loads it may be necessary to take readings every 1 min. or even at shorter intervals.

42. An Ammeter for Direct-current Line, Maximum-demand Measurements is diagrammed in Fig. 12. This may be utilized on either direct-current aerial line wires or on single-conductor cables without its being necessary to open the conductor under test. The device may be considered as comprising two essential components; the exploring coil, *C*, and the meter, *M*. The meter, *M*, consists of four elements: (1) *an ammeter, I*, which is actuated by the current flowing from the battery through the fine-wire winding, *W*, of the exploring coil; (2) *a variable resistor, R;* (3) *low-voltage battery, N;* and (4) *a flux polarity indicator, P*.

OPERATION.—When used to determine the current in the conductor the hinged section of the exploring coil is opened and the coil is placed so as to encircle the conductor. The current, in the conductor *A* under test, creates a magnetic field in the core of the exploring coil. This flux will, provided the coil has been placed over the conductor under test in the proper direction, cause the indicating magnet, which is mounted in a small air gap, to move in a clockwise direction establishing a contact at *B* and permitting current from the battery to flow through the winding of the relay on the instrument.

This causes the flux polarity indicator to move toward the right, showing the observer that the indicating magnet is, because of the influence of the flux due to *A*, making a contact with *B*. Now, current is permitted to flow from the battery through the ammeter winding of *M* and through the fine-wire winding on the exploring coil and this current is varied by adjusting the variable resistor, *R*, until the counter flux, due to the battery, just neutralizes the flux due to the current in the conductor *A*.

When this occurs the indicating magnet will swing out of contact with *B* and the flux-polarity indicator will notify the observer thereof and the current read on the ammeter scale, *I*, of the instrument *M* will indicate directly, or will be proportional to, the current flowing in *A*. The exploring coil may be used at any reasonable distance from the meter provided the number of cells in the battery is correspondingly increased.

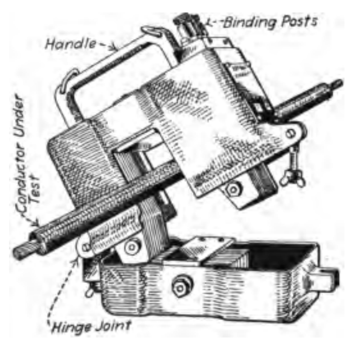


FIG. 13.—Portable transformer open, cable having been inserted.

43. For Determining the Maximum Demand in Alternating-current Lines the currents flowing in the line can be ascertained with a portable testing transformer such as that illustrated in Figs. 13 and 14. The complete outfit (Fig. 14) consists of an alternating-current ammeter, a split-type current transformer and a suitable flexible lead for the interconnection of the two devices. To measure the current in the conductor the transformer is opened (Fig. 13) then closed around the conductor, after which the ammeter (which has been properly calibrated for use with the transformer by its manufacturers) will indicate the current intensity in the conductor under test.

44. For Determining Maximum Demand with a Graphic Wattmeter or Ammeter it is merely necessary to examine the graphic record produced by the instrument for the period under consideration and thereby find, by inspection, the greatest power demand that has occurred in any time interval of the prescribed duration. Fig. 7 shows a typical record from a graphic ammeter while Fig. 8 shows that from a wattmeter. These illustrations have been referred to in preceding paragraphs.

45. A Westinghouse RO Demand Meter is shown in Figs. 15, 16 and 17. This might be called a lagged-type in stru-

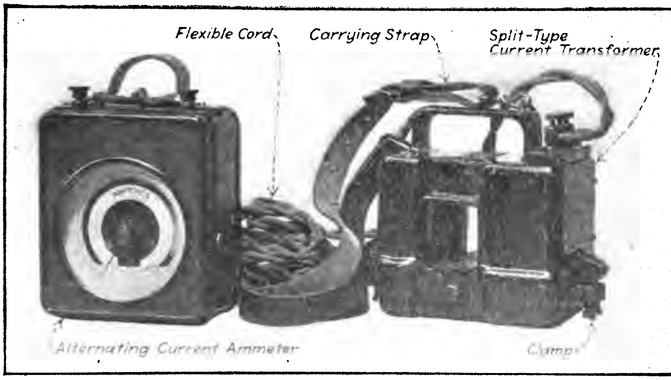


FIG. 14.—Portable outfit for the determination of current in alternating-current lines.

ment, inasmuch as the movement of its demand pointer is retarded by the action of an escapement wheel (*F*, Fig. 17). It is made only for alternating-current service. The general operating principle is the same for the single-phase as for the polyphase meter. These instruments are installed in the same manner as are ordinary watt-hour meters, no additional apparatus or wiring being required. Each device consists of an induction watt-hour meter to which is added the maximum-demand-meter mechanism. The maximum demand, in kilowatts, is indicated by the pointer, which moves over the 4-in. dial. The integrating energy is registered in kilowatt-hours on the four-dial counter.

CONSTRUCTION.—An auxiliary aluminum disc (*A*, Fig. 17) mounted in the air gap of the watt-hour meter electromagnet is provided to drive the maximum-demand pointer *P*. The speed of movement of the pointer is, through gearing, retarded by the main disc. In fact, as its maker states: The mechanism is very similar to that of an ordinary clock. The auxiliary disc (*A*, Fig. 17) performs a function somewhat similar to that of a main spring, in that it furnishes power for driving the demand pointer and the escapement *F*, while the rate of progression of the demand pointer, *P*, is controlled by motion of the main disc—which performs the function of a balance wheel. It is, then, to be observed that the function of the main watt-hour-meter disc is, insofar as the demand mechanism is con-

FIG. 15.—Single-phase watthour demand meter (Westinghouse Type RO).

FIG. 16.—Polyphase watthour demand meter (Westinghouse Type RO).

cerned, simply to regulate the rate of deflection of the auxiliary disc *A* and the progression of the demand pointer. The main disc supplies no power to the maximum-demand mechanism except the negligible amount required to oscillate the escapement claw.

46. The Principle of Operation of the RO Demand Meter is this: When energy flows through the meter, the main watt-hour-meter disc (*B*, Fig. 17) is forced to rotate the same as in any alternating-current watt-hour meter. Its rotational speed is, obviously, proportional to the load. The auxiliary disc *A*, which drives the maximum-demand pointer, will also tend to rotate. However, its unrestricted rotation is prevented by

the action of the escapement wheel F. Now, the main disc, driving through gears JH and I (which have no connection with the auxiliary shaft) oscillates the escapement by means of the cam G. Thus, the auxiliary disc is permitted to swing, but at a speed proportional to the load. As the escapement claw oscillates, the teeth of the escapement wheel are allowed to pass, one by one, until the tension of the spiral spring C balances the rotating torque of the auxiliary disc. The mechanism is then in equilibrium, the demand pointer indicating the load. But although the main disc may continue to rotate

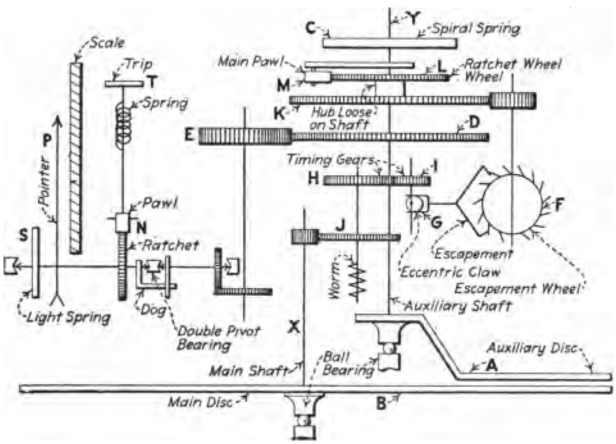


FIG. 17.—Diagrammatic representation of mechanism of Westinghouse Type RO demand meter.

so long as the load is maintained, no further deflection of it (or of the demand-indication pointer which it drives) occurs, since the escapement claw is now oscillating freely between the teeth of the escapement wheel.

NOTE that the escapement wheel F is not driven directly from the auxiliary shaft by gear K. It is driven by a ratchet wheel L mounted on a sleeve, which is loose, on the auxiliary shaft and to which the gear K is attached. This ratchet wheel is propelled by a pawl carried by an arm fixed to the auxiliary shaft. This device causes the deflection of the auxiliary disc to be retarded by the escapement wheel when the pointer is advancing across the scale, but allows the disc to drop back freely to equilibrium when the load is reduced. Hence, the auxiliary disc will

always tend to follow the variation in load; at the same time the demand pointer will always indicate the maximum demand up to the instant at which the instrument was observed.

To reset the instrument, the resetting button T is pressed. This raises the pawl from the ratchet and the pointer is then, by the action of the spiral spring S, returned to zero or to the position of the auxiliary disc.

47. The Time-element Feature of the RO Demand Meter may be explained thus: When any constant load is being metered by the instrument, the time required for the auxiliary disc to reach equilibrium is constant. Thus, assume that the demand meter is so calibrated and adjusted that it requires just 15 min. to reach equilibrium when the constant power load being metered is 500 watts. Then, if this 500-watt load is discontinued and the meter cut into a circuit carrying a 1,000-watt load it is obvious that the demand pointer will deflect over exactly twice the angle obtaining with a 500-watt load, however, the main disc is now rotating at twice its former speed. Hence, the pointer will attain equilibrium in the same time interval (15 min.) as with the 500-watt load.

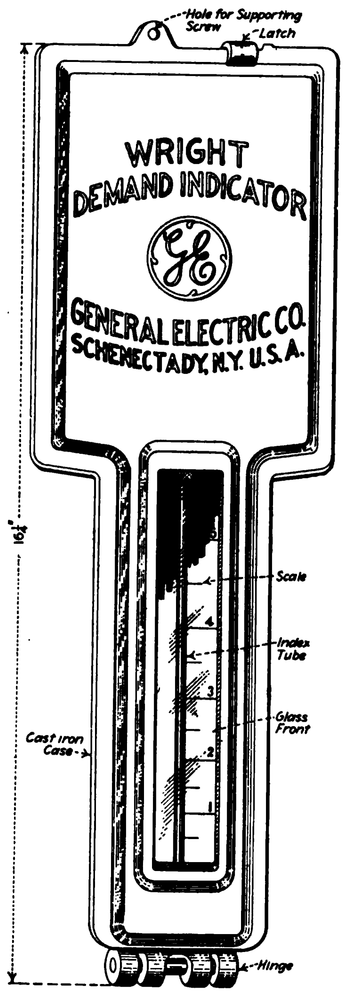


Fig. 18.—The Wright demand meter.

48. The Wright Demand Meter (Figs. 18 and 19) might be classed as a thermal-type lagged instrument. It indicates ampere only and not kilowatt demands. The principle is diagrammed in Fig. 19. The current, or the shunted part

thereof, to be metered, flows through the resistor coil of platinoid, C, which is wound around an enlargement A of a U-shaped hermetically sealed glass tube. The tube is partially filled with sulphuric acid or similar fluid. When current flows through C, the resistor is heated thereby. The air within the bulb A is expanded which forces the liquid to rise in the leg L. If the liquid rises above a certain height, H, it flows over into the small graduated index tube. The quantity of liquid which flows into the index tube may be taken to indicate the maximum demand. If the index tube has uniform bore the height of the liquid in it will then be a measure of the square of the maximum current. In the actual instrument the divisions increase in spacing from the bottom up. After having been read, the meter can be reset by tilting the tube, allowing the liquid to flow back into B. These meters may be used on either alternating or direct-current circuits and while they have some disadvantages there are a great many of them in use. The design of the device has not been altered materially in years. Since the air in the tube heats gradually the instrument provides a certain time lag. Its manufacturers state that if a steady over-demand continues for 5 min., 80 per cent. of the load will be indicated; 10 min., 95 per cent.; 30 min., 100 per cent.

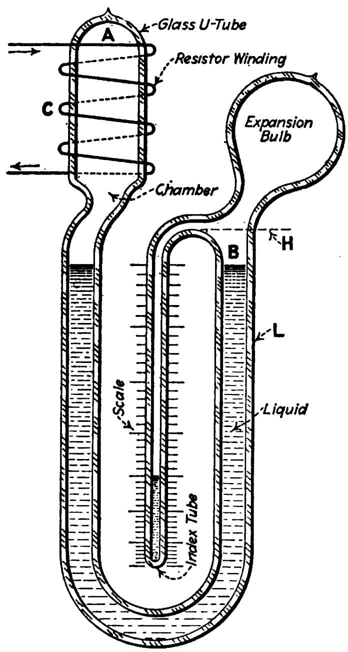


FIG. 19.—Illustrating the principle of operation of the Wright demand meter.

49. Thermal or Thermostatic Meters of several different types have been proposed. In these the movement of the demand-meter pointer is usually actuated by the expansion

of the fluid or gas. They are all classed as lagged-type instruments. Figs. 9 and 10 show typical characteristic curves for instruments of this general character, which were designed or calibrated for 15-min. and 30-min. time intervals, respectively.

50. Of the Integrating Indicating Demand Meters the General Electric Company's M–4 for alternating-current and M–5 for direct-current service (Figs. 20, 21 and 22) are typical. These demand meters operate in conjunction with a watt-hour meter, substantially as suggested in Fig. 22. The demand-indicating element is driven electrically from the register of the watt-hour meter. Fig. 21 diagramming the mechanism of an alternating-current meter, illustrates the general principle.

FIG. 20.—Alternating-current demand meter diagrammatic representation of which is shown in Fig. 21 (General Electric Co., Type M-4).

OPERATION.—A contact C (Fig. 21) is mounted on the watt-hour meter. It completes contact each time the watt-hour meter has made a certain number of revolutions, that is, every time a certain number of kilowatt-hours of energy has been registered by the watt-hour meter. Whenever C contacts, operating coil O is energized and pulls over its armature. This advances ratchet R one notch. In this way the friction pointer is propelled forward—the motion being transmitted by the ratio gears—as energy is consumed in the circuit being metered. The friction pointer is not rigidly connected to shaft S, but is pushed by the dog D, which is rigidly connected to S. It follows that the position of the dial-pointer on the scale is determined by the energy consumption registered by the watt-hour meter.

However, so that the readings of the demand meter will—to satisfy the definition of maximum demand quoted above—indicate the demand over a definite time interval it is imperative that the dog D which drives the friction pointer over the scale shall be reset to the zero position at the end of the specified time interval. But the dial pointer must be permitted to remain at the most advanced location on the dial scale to which it has been forced by the dog. The mechanism of this timing feature is this:

The aluminum disc *M* (Fig. 21) in the demand meter (which is rotated by the field produced by an alternating-current electromagnet) is similar to the disc in any alternating-current watt-hour meter and is caused to rotate by the same magnetic reactions as those which rotate the disc in

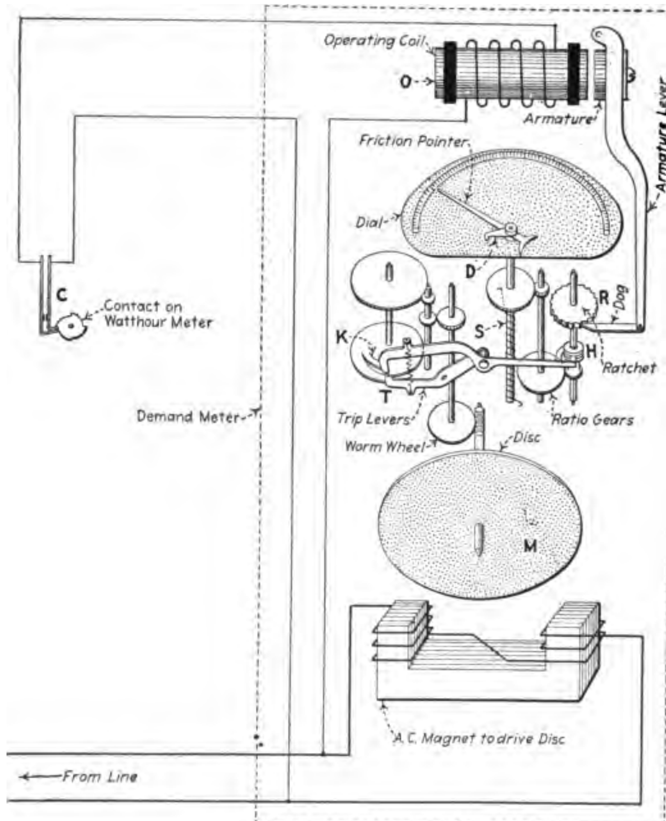


FIG. 21.—Diagrammatic representation of operating mechanism of alternating-current demand meter. (General Electric Co., Type M-4, Form AA). The corresponding direct-current meter (Form BA) is similar except that the disc and shaft is replaced by a clock mechanism.

such a watt-hour meter. Now, since the torque against which the disc is working is constant and since the frequency of the alternating current is constant, the disc always rotates at a constant speed.

The mechanism is so designed and calibrated that at the end of each of the time intervals for which the meter has been adjusted (for example

at the end of each 15-min. interval or the end of each 30-min. interval) the trip levers *T*, by the action of the cams *K*, will be pulled together by

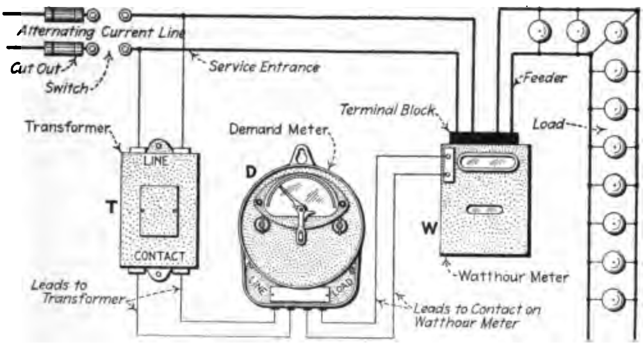


FIG. 22.—Method of connecting alternating-current demand meter for 440 and 660-volt loads. For 110 and 220-volt loads, and for direct-current loads the transformer is omitted.

the small spring in tension between them. The cams *K* are caused to rotate at a uniform speed by disc *M* which drives through the gearing shown. When the trip levers are pulled together the clutch at *H* is released and the spring *S* will return the dog *D* to the zero position. But the friction pointer will remain where it was. Hence, the dog is thus returned to zero at the end of each of the prescribed time intervals. It is obvious, then, that the direction pointer will—assuming that its scale is properly calibrated—always indicate the maximum demand for the period during which the meter has been in operation.

FIG. 23.—Printometer-type demand meter (General Electric, Type P, Form AA).

After the maximum-demand reading for the period—for example, for a month—under consideration has been taken, the demand pointer is returned to the zero position by the meter reader. He unseals the resetting device and turns the handle.

The direct-current demand meter (M–5) of this general type is similar to the alternating-current except that instead

of the timing mechanism being controlled by an aluminum disc, which is rotated by an alternating-current magnetic field, it is rotated by a clockwork within the demand meter.

51. Printometer-type Demand Meters are made for both alternating and direct-current service. The printometer (Fig. 23 and *P*, Fig. 24) is not of itself a meter, but is merely

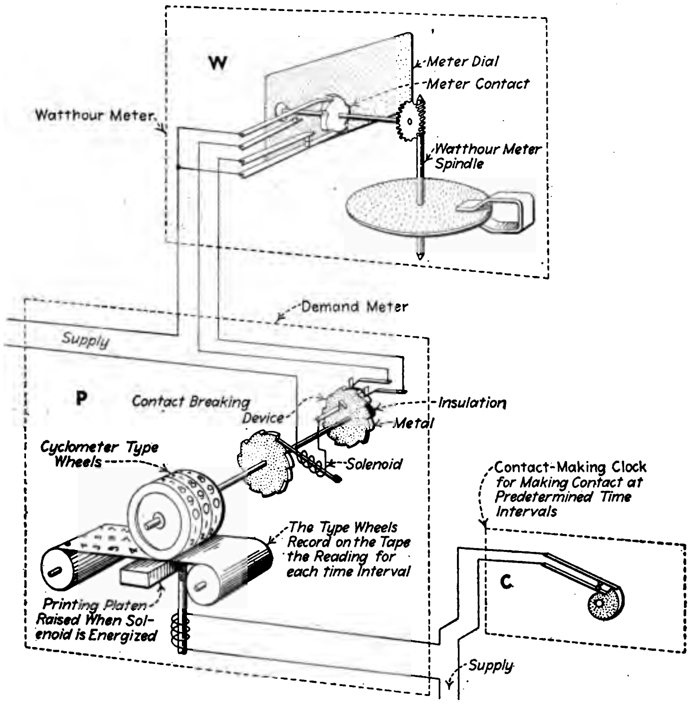


FIG. 24.—Diagrammatic representation of operating mechanism of printometer-type demand meter.

a registering device used in combination with a standard watt-hour meter (*W*, Fig. 24) and a contact-making clock (*C*, Fig. 24 and Fig. 25). These illustrations show the General Electric Company's Type *P*–2 instrument. Printometer records are printed on paper strips, a part of one of which is shown in Fig. 26. This record shows the total energy consumption as registered by the watt-hour meter. It also shows

the time of day at which the various blocks of energy between any two successive printings were consumed. The maximum demand can be readily determined from the tape record (Fig. 26) which also will indicate the hour and date upon which it occurred.

OPERATING PRINCIPLE.—As energy flows through the watt-hour meter W (Fig. 24) the meter contact is successively closed and opened and, whenever it is closed, current flows through the solenoid in P and its plunger forces the cyclometer type wheels ahead a notch. The mechanism is so arranged that the type wheels are moved forward at a rate equal to the rate of flow of energy through the watt-hour meter. The upper-most figures on the type wheels give at any instant a reading in kilowatt-hours equivalent to that indicated by the watt-hour meter dial.

FIG. 25.—Contact-making clock or contactor for printometer-type demand meter.

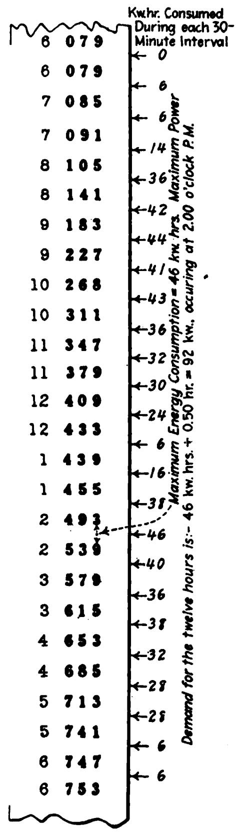


FIG. 26.—A twelve-hour record from a "printometer" demand meter (General Electric Co., Type P). Illustration is exactly half actual size.

The contactor C (Fig. 24) on the clock makes contact at the predetermined time intervals (for example, every 15 min. or every 30 min.) and each time that it does the kilowatt-hour consumption up to that instant is recorded on the tape as shown in Fig. 26. Simultaneously the

time of day at that instant is printed on the tape. Thus the record shown in Fig. 26 is obtained. The watt-hour-meter contact shown at W (Fig. 24) can be attached to any watt-hour meter. Where the printometer is to be used in making tests at a number of different locations a portable outfit similar to that of Fig. 27 is convenient.

52. An Integrating Graphic Demand Meter (General Electric Company's Type G–2) is shown in Figs. 28 and 29. The chart or record produced by this device is reproduced in Fig. 30 and the method of connecting it in Fig. 31. The

FIG. 27.—Printometer-type demand meter arranged in self-contained case for field tests.

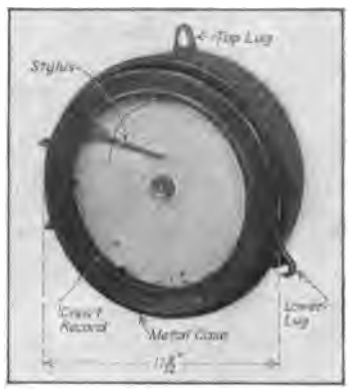


FIG. 28.—A graphic demand meter (General Electric, Type G–2).

demand-meter movement is controlled by a watt-hour meter with which it is electrically interconnected (Fig. 29). The contactor, which is mounted on the watt-hour-meter register W, closes the control circuit at intervals, the frequency of which is determined by the speed of rotation of the watt-hour-meter disc, that is by the rate of energy consumption in the metered circuit.

OPERATION.—Each time the contactor closes the control circuit, the operating coil in the demand meter G (Fig. 29) is energized and its arma-

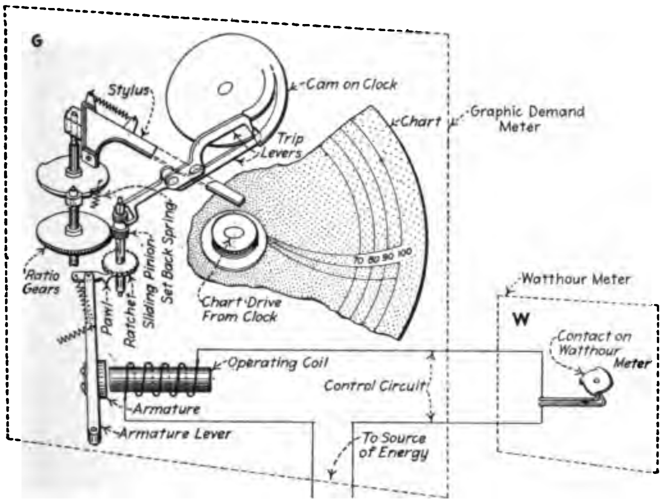


FIG. 29.—Schematic diagram of mechanism of graphic demand meter.

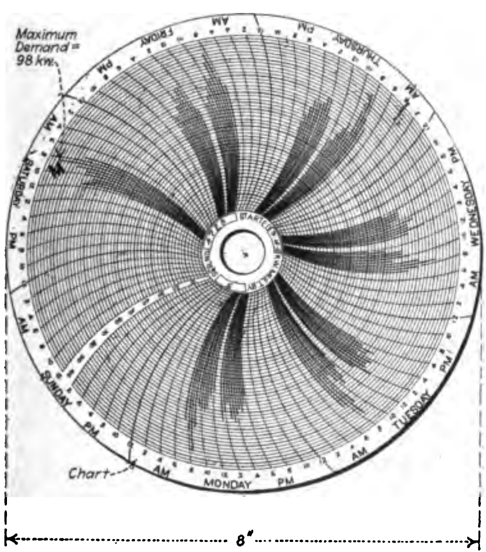


FIG. 30.—Graphic record produced by the General Electric Company's Type G demand meter of Fig. 23.

ture lever is attracted. This moves the ratchet wheel forward a notch. When the contactor opens, the coil is deënergized and the lever is pulled back by its spring—ready for another push. The stylus is moved upward a certain distance each time the contactor closes, the motion being transmitted to the stylus through the gear train shown.

As energy is consumed in the metered circuit and the contactor opens and closes, the stylus is forced upward "step by step" across the chart until the end of the time interval for which the meter has been adjusted. At the end of each time interval, the cam (which is driven by the clock within the meter which also rotates the chart) has rotated to such a position that the first of the trip levers falls. This disengages the sliding pinion from the gear in which it normally meshes, which permits the setback spring to pull the stylus mechanism to the zero position.

As the rotation of the cam is continued, the second trip lever is permitted to drop which returns the sliding pinion to its normal position and

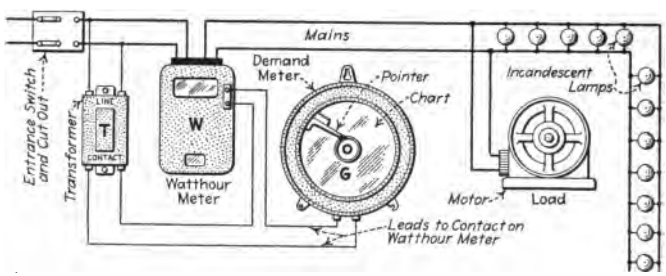


FIG. 31.—Method of connecting alternating-current graphic demand meter for 440-volt circuits. For 220 and 110-volt alternating-current loads and for direct-current loads, the transformer is omitted.

again completes the gear transmission system between the armature lever and the stylus. This having been effected the demand-meter movement is in trim to again drive the stylus over the chart during the next time interval.

Since the clock within the demand meter rotates the chart at constant speed, the stylus will travel a different course over the chart during each time interval as shown in Fig. 30. In any time interval the distance (measured along the curved line which it draws) of the stylus from the zero circle of the chart is, at any instant, directly proportional to the number of kilowatt-hours energy registered by the controlling watt-hour meter during that interval. Hence, the ends of stylus-record lines indicate the demands for the different intervals. The end of the longest stylus-record line indicates the maximum demand. Thus, the maximum demand for the period comprehended by the graph of Fig. 30 is (at M) 98 kw.

52a. The Westinghouse Recording-demand Watt-hour Meter is shown in Figs. 32 and 33. This instrument combines

FIG. 32.—The Westinghouse Type RA demand watthour meter.

FIG. 33.—The mechanism of the Westinghouse Type RA demand watthour meter.

in one unit a watt-hour meter and a demand meter. It indicates,* on a four-dial counter, the total kilowatt-hours

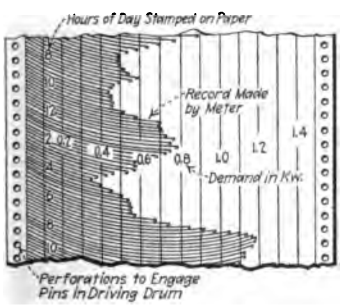


FIG. 34.—Record of a 15-minute-interval RA meter.

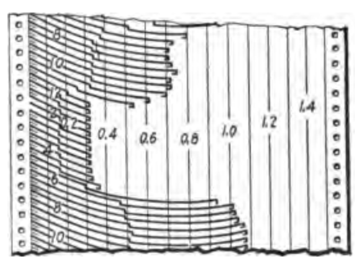


FIG. 35.—Record of a 30-minute-interval RA meter.

energy consumption and records, on a strip or ribbon of paper (Figs. 34 and 35), the integrated kilowatts demand over successive predetermined time intervals.

* Westinghouse Electric & Manufacturing Company.

PRINCIPLE OF OPERATION.—Under load, the gear train of the watt-hour meter advances the counters in the regular manner. At the same time the gear train causes the ink-carrying pen to advance across the record paper in proportion to the energy registered. At the end of a predetermined time interval a stud on the reset wheel releases the pen gear from mesh with the gear train and a balancing weight returns the pen to zero, where it is again meshed with the gear train to repeat its advance during the next time interval.

Just before the pen gear is released, the record paper is advanced 1⁄16 in. by the operating spring so that the pen makes a distinct and readily observed record of the maximum pen travel. This record shows both the amount of integrated demand and (by the time calibration printed on the record paper) the time of its occurrence. The meter may be geared for 15, 30 and 60-min. time intervals.

53. Demand Factor* is "the ratio of the maximum demand of any system or part of a system, to the total connected load of the system or that part of the system under consideration." It is expressed as a percentage. Thus, to obtain the "demand factor" of any installation, divide the maximum demand (usually expressed in watts or in kilowatts), imposed by the connected load, by the connected load (correspondingly expressed in watts or in kilowatts). Thus:

$$\text{(7)} \qquad \textit{Demand factor} = \frac{\textit{maximum demand}}{\textit{connected load.}}$$

$$\text{(8)} \qquad \textit{Maximum demand} = (\textit{demand factor}) \times (\textit{connected load}).$$

$$\text{(9)} \qquad \textit{Connected load} = \frac{\textit{maximum demand}}{\textit{demand factor.}}$$

54. The Explanation of "Demand Factor" will now be considered: It is seldom that the kilowatt or kilovolt-ampere maximum power demand of a *group* of electrical devices or "receivers" is equal to the sum of the kilowatt or kilovolt-ampere ratings or capacities of the receivers. There are two reasons for this condition. *First:* Electrical apparatus is frequently selected of a size greater than is actually necessary to perform the duties imposed on it. That is, excess overload or reserve capacity is provided. *Second:* In a group of electrical devices, it does not often occur that all of the devices will,

* A. I. E. E. STANDARDIZATION RULES.

at the same time, be imposing the maximum loads which each *can* impose on the supply circuit.

NOTE.—It follows from the definition of demand factor recited above, that demand factors are most often less than 100 per cent. Sometimes, however (see accompanying tables), 100 per cent. demand factors are encountered. Also, demand factors may be, and sometimes are, greater than 100 per cent. Where such a condition exists, some of the receiving apparatus must, obviously, be overloaded.

55. The Determination of a Demand Factor can be readily effected if the two values: (1) *The Maximum Demand* and (2) *The Connected Load*, are known. Hence, in finding the demand factor of an existing installation, its maximum demand must be measured—ascertained by test—by following one of the methods hereinbefore described. Then the connected load can be computed by adding together the nameplates or manufacturers' ratings of all of the receiver devices in the installation. The values thus obtained may then be substituted in equation (4) and the problem solved. Some of the examples under Art. 58 illustrate the process. In designing new installations where it is necessary to know the maximum demands, the designer must assume demand factors, basing his assumptions on values which tests have shown to obtain under similar conditions in practice. The values given in the following tables may be used as a basis for such assumptions.

56. In Determining Demand Factors of Direct-current Circuits it is, where feasible, desirable to reckon the connected load and the maximum demand in watts or in kilowatts. However, where the maximum demand can be more conveniently ascertained in amperes, then the connected load is taken as the sum of the full-load current (in amperes) inputs of all of the devices in the group under consideration. In such cases it is assumed that the voltage impressed on the multiple "constant-potential" circuit remains constant. Where the maximum-demand values have been observed by test with a direct-current, line-testing ammeter, like that of Fig. 12, the connected load is most conveniently taken in amperes.

57. In Determining Demand Factors of Alternating-current Circuits the maximum demand may be observed in either

kilowatts, kilovolt amperes, or amperes—depending upon the methods and instruments used for measuring the maximum demand. All of the maximum-demand meters now on the market, except those of the thermal types, indicate the maximum demand in watts or in kilowatts. Where ammeters, similar to those of Figs. 13 or 14 are used, the maximum-demand value thereby obtained is, obviously, in amperes. The thermal-type demand meters usually read in amperes. Where the maximum demand is measured in amperes, it is multiplied by the impressed voltage to obtain the kilovolt-ampere equivalent.

NOTE.—The connected load may be reckoned in either kilowatts or kilovolt-amperes. It is however, usually reckoned in kilowatts because most receiving devices are rated in kilowatts—or in watts or horse-power, both of which may be directly reduced to kilowatts.

Hence, it follows that the demand factor of an alternating-current circuit may be taken as either: (1) (*kw. max. dem.*) ÷ (*kw. con. load*), or (2) as (*kva. max. dem.*) ÷ (*kw. con. load*). It is, in general, the kilovolt-ampere demand rather than the kilowatt demand which determines the capacity of—hence, the investment required for—the electrical equipment required to serve a given load. Hence, the second method (*kva. max. dem.*) ÷ (*kw. con. load*) appears to be the more logical one. It is the one which must, directly or indirectly, be used where the maximum-demand determination is made to provide a basis for the selection of equipment and plant to serve a load. However, since most demand indicators indicate kilowatts instead of kilovolt-ampere electricity rate schedules are, probably, most often based on a "(*kw. max. dem.*) ÷ (*kw. con. load*)" demand factor. In such cases the feature of the power factor of the load is recognized in some arbitrary way in the rate schedule which is compiled to apply.

58. How Demand Factors are Used is illustrated in the examples which follow. Broadly, demand factors have only one general application, that is, to determine the capacity—hence cost—of the apparatus which will be required to serve a given load. As above suggested, they are also used in computing rate schedules but they should be factors in such computations only because of their influence on the required investment.

EXAMPLE.—A certain residence has a connected load as follows: four 60-watt lamps, twenty 40-watt lamps, six 10-watt lamps. With a

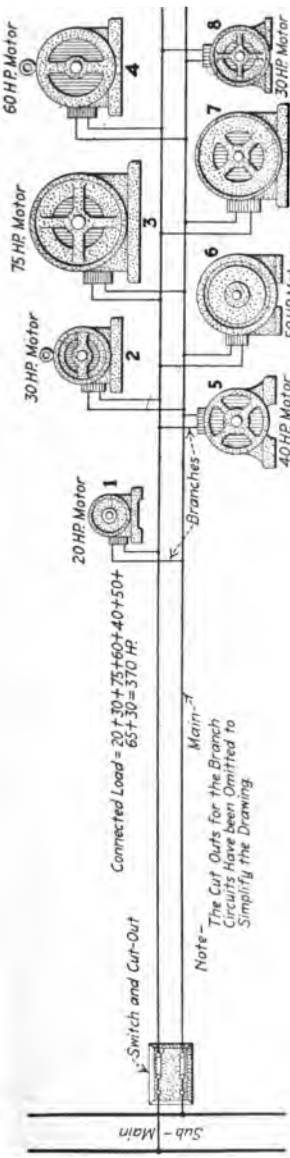


FIG. 36.—Example in computing the maximum demand of a motor circuit of known connected load.

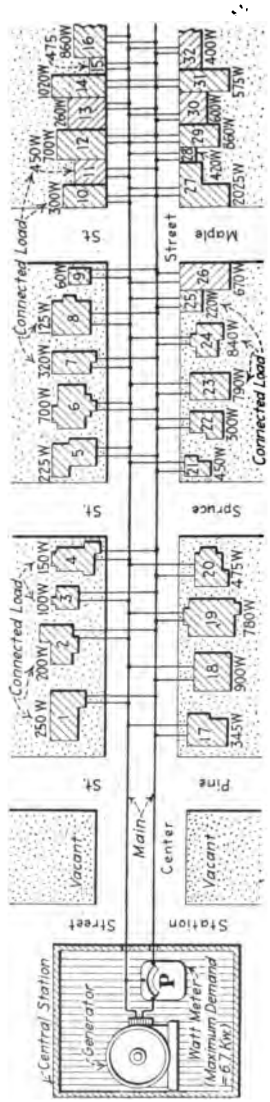


FIG. 37.—Illustrating the meaning of demand factor as applied to a group of consumers.

demand meter it is observed that the 30-min. maximum demand is 638 watts. What is the demand factor of this installation? SOLUTION.—Connected load is: $(4 \times 60) + (20 \times 40) + (6 \times 10) = 240 + 800 + 60 = 1{,}100$ watts. Then substituting in equation (7) *Demand factor* = (*maximum demand*) ÷ (*connected load*) = 638 ÷ 1,100 = 0.58. Hence, the demand factor of this installation on the basis of a 30-min.-interval maximum demand is 58 per cent.

EXAMPLE.—The connected lighting load in a large theatre is 3.6 kw. What will, probably, be the 30-min. maximum demand? SOLUTION.—The probable demand factor for a large theatre lighting load is (Table 61) 60 per cent. Hence, substituting in the equation (8): *Maximum demand* = (*demand factor*) × (*connected load*) = $0.60 \times 3{,}600 = 2{,}160$ *watts*. Hence, the 30-min. maximum demand would be, probably, about 2.2 kw.

EXAMPLE.—In Fig. 36 is shown a group of motors representing a total connected load of 370 h.p. Assuming that for installations of this character the demand factor is known to be 55 per cent., what is the maximum demand? SOLUTION.—In equation (8): *Maximum demand* = (*demand factor*) × (*connected load*) = $0.55 \times 370 = 203.5$ *h.p.* Now, $203.5 \times 0.746 = 152$ *kw.*, which is the maximum demand.

EXAMPLE.—In Fig. 37 the total connected load, that is, the sum of the watts load installed in all of the buildings, is 16.75 kw. The maximum demand indicated by the wattmeter P, that is, the greatest demand ever indicated by this instrument is 6.7 kw. What is the demand factor for this load? SOLUTION.—Substitute in (7): *Demand factor* = (*maximum demand*) ÷ (*connected load*) = 6.7 ÷ 16.75 = 0.40 = 40 per cent. Hence, the demand factor for this group of consumers is 40 per cent.

EXAMPLE.—In a certain town of 1,000 inhabitants in Missouri served by an alternating-current plant the connected load, motors, lamps and all receiving devices totals 55 kw. The 30-min. maximum demand is 20.8 kva. What is the demand factor for the system? SOLUTION.—Substitute in equation (7): *Demand factor* = (*maximum demand*) ÷ (*connected load*) = 20.8 ÷ 55 = 0.38. Hence, the 30-min. interval demand factor for this installation is 38 per cent.

59. The Tables of Demand Factors which are given herewith are intended merely to serve as guides. While it is believed that they represent average conditions they must be used with judgment. The only certain way to determine demand factors for specified conditions is to ascertain them by test. It is as impracticable to arrange a table of demand factors which will cover all conditions as it would be to compile a schedule indicating what kind of a hat a woman of a certain complexion and nationality would probably buy under

given conditions. However, where test values are unknown the factors tabulated (Tables 61 to 65) should be of service in designing new installations and plants.

60. Demand Factors for Lighting Installations are reasonably constant for each of the different classes of service. For example, the demand factor for saloons will usually be in the neighborhood of that indicated in Table 61; that is, about 70 per cent. Furthermore, these lighting-installation demand factors would be about the same for a given installation from week to week. Lighting loads are not subject to the sudden pronounced variations that occur with power demands. Hence, the demand factor for a lighting load determined on a 30-min.-interval basis will be about the same as one determined for the same load on a 15-min.-interval basis.

61. Approximate Demand Factors for Miscellaneous Lighting Service.—Factors are based on observed data from a number of sources on a 30-min.-interval maximum demand. The following factors apply to one consumer only. That is, to obtain the "30-min." maximum demand of *one* consumer of any of the given classes, multiply his connected load in watts by the corresponding demand factor. Factors determined on a 15-min.-interval basis would not, probably, differ materially from those given.

Class of lighting service	Demand factors in per cent.	
	Probable range	Probable fair average value
Sign, outline, display and window lighting	90–100	100
Theatres (small)	70–90	75
Offices (business and professional)	55–90	70
Banks	55–85	70
Saloons	60–90	70
Restaurants	50–80	70
Laundries	60–75	70
Lodge and dance halls	65–90	70
Depots (railway stations)	75–95	70
Shops (barber shops and the like)	55–80	70

Class of lighting service	Demand factors in per cent.	
	Probable range	Probable fair average value
Stores	40–95	65
Pool and billiard rooms	40–70	65
Printers and engravers shops	30–75	60
Theatres (large)	40–75	60
Churches and auditoriums	55–85	60
Factories	45–60	55
Livery stables	50–60	55
Schools used at night	35–55	50
Machine shops	25–60	45
Hospitals	25–60	45
Warehouses	20–45	40
County, federal and municipal buildings	30–40	35
Universities and colleges	20–50	30

62. Approximate Demand Factors for Small Lighting Consumers.—The following factors are those said to be used in Chicago for computing rates for small lighting customers. They may be taken as fairly representing average small-lighting-customer conditions. It is understood that these factors are based on a large number of observations made with Wright demand meters. They are, therefore, approximately, on the basis of a 15-min.-interval maximum demand. However, it is likely that, for this class of service (lighting service), the demand factors would not be materially different from those tabulated if they were based on a 30-min.-interval maximum demand.

Connected load, watts	Demand factors, per cent.			
	*A** Chicago values used for computing rates of small consumers		*B** Values of graph of Fig. 38, averaged from Chicago values	
	Commercial	Residence	Commercial	Residence
250	100	100	100	100
300	100	89	100	93
350	95	86	94	86
400	91	83	91	80
450	89	74	88	85
500	87	73	86	71
550	85	67	84	67
600	83	67	83	65
650	82	61	82	62
700	81	61	81	60
750	80	57	80	58
800	79	57	79	57
850	78	55	78	56
900	78	55	78	54
950	77	53	77	53

* The values in the columns headed *A* are those which have been used in Chicago. These values were plotted in Fig. 38. Then the smooth curves were drawn through them. The average taken from these smooth graph values are given in the columns headed *B*.

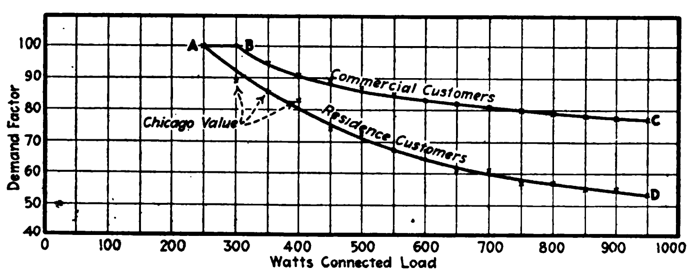


FIG. 38.—Graph showing relation of demand factor of small consumers to connected load.

63. Demand Factors for Motor Installations are subject to considerable variation and hence, should, in all important

studies, be determined by test. To be of material value such test should extend over an extended period because experience has shown that the demand of motor loads may be very much greater on certain days or months than on others.

64. Approximate Demand Factors for Alternating-current Motor Installations.—Factors are based on observed data from a number of sources on a 30-min.-interval maximum demand. In this table it is assumed that (equation 7): *Demand factor* = (*maximum demand in kva.*) + (*connected load in kw.*). Because of the large starting currents taken by alternating-current motors the demand factors involved are liable to be rather high.

Class of service	Number of motors in installation	Total motor horsepower of installation	Demand factors in per cent.	
			Probable range	Probable fair average value
Single-phase and three-phase alternating-current motors......	1–10	1–75	80–110	90
General factory and other service	10–20 and over	1–150	75–95	85
Small single-phase motors......	1–20	1–50	80 –100	90
Alternating-current elevator and crane motors.	1–2	....	90–110	100
	3–5	....	60–80	70
	over 5	....	50–70	60

65. Approximate Demand Factors for Direct-current Motor Installations.—Factors are based on observed data from a number of sources on a short-time interval maximum demand. In this table (equation 7): *demand factor* = (*maximum demand in kw.*) + (*connected load in kw.*).

Class of service	Number of motors in installation	Total motor horse-power of installation	Demand factors in per cent.	
			Probable range	Probable fair average value
Direct-current motors, general factory and other service	1	1–5	75–95	85
	1	6–10	65–85	75
	1	11–20	55–75	65
	1	over 20	50–70	60
	2	1– 5	70–90	80
	2	6–10	65–85	75
	2	11–20	60–80	70
	2	over 20	45–65	55
	3–5	1– 5	60–80	70
	3–5	6–10	55–75	65
	3–5	11–20	50–70	60
	3–5	over 20	40–60	50
	6 and over	1– 5	55–75	65
	6 and over	6–10	50–70	60
	6 and over	11–20	45–65	55
	6 and over	over 20	25–55	45
Machine shop individual drive	10 and over	over 20	35–60	40
Elevator and crane motors	1–2	....	90–110	100
	3–5	....	60–80	70
	over 5	....	50–70	60

66. The Importance of Maximum Demand and Demand Factor in Determining Suitable Transformer Capacities is a thing that is not ordinarily given the consideration which it deserves. The usual tendency when installing transformers serving individual loads—and those for serving group loads for that matter—is to select transformers of capacities considerably larger than is actually necessary. Hence, where a transformer is to be installed some sort of a study should always be made to ascertain the facts and determine the consumers actual maximum demand. It will be found that in

the long run such a course will be justified by the saving in fixed charges and operating expenses which will result.

NOTE.—Where transformers are larger than actually necessary, the interest charge is greater than it should be and there are also superfluous charges due to excessive electrical losses which, in the aggregate, may be considerable. Where a group of consumers is to be served by a transformer it is desirable to base the capacity of the transformer to be installed on the diversity factor (Art. 70) of the consumers as well as on their demand factors.

SECTION 4

DIVERSITY AND DIVERSITY FACTORS

67. Diversity, as defined in the dictionary, "is the state of being dissimilar to one another." There is a "diversity" or difference among: (1) *the characteristics of the different loads of the same general class;* and (2) *the various general classes of loads* which a central station system may be called upon to

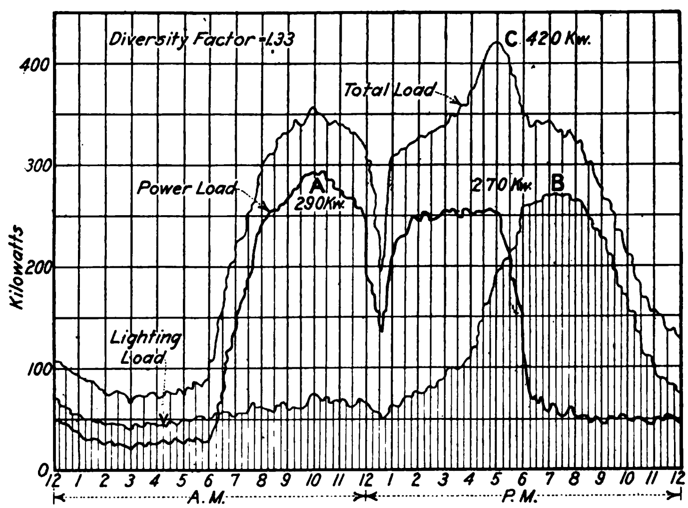


FIG. 39.—Graph showing diversity between power and lighting loads.

serve. And, as will be shown later, it is, from an economic aspect, extremely fortunate that such is the case. In central-station parlance, the term "diversity" is used to signify *diversity of demand*—to imply that the maximum demands of the various consumers of the different classes and of the different circuit elements in an energy-distribution system are not coincident. That is, their different maximum demands occur at different times, and not simultaneously.

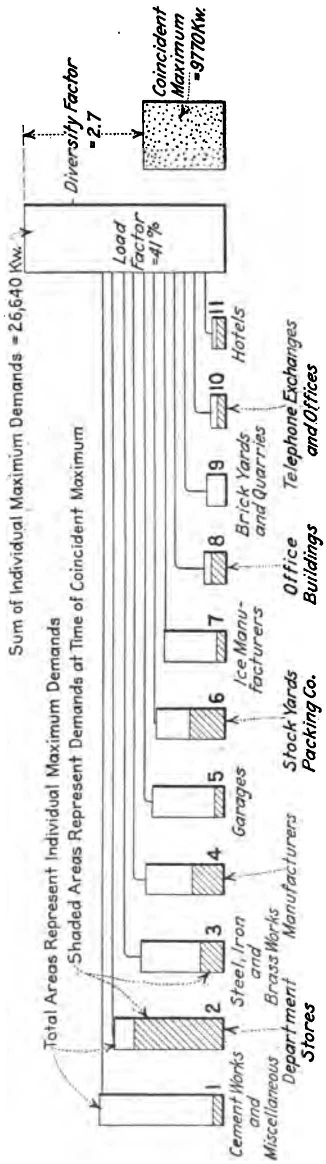


Fig. 40.—Indicating graphically how the diversity factor for 82 large light-and-power customers in Chicago was 2.7 per cent.

For Illustration.—It is obvious that the residence-lighting load will attain its maximum in the evening, whereas a manufacturing establishment will ordinarily require the greatest power during the daylight hours. Again, commercial establishments of certain types, for example department stores, generally use much more power during the day than in the evening, while stores of other sorts, such as drug stores, 'use more in the evening. A similar condition holds for the different sorts of manufacturing establishments. Hence, there is a *diversity of demand* among these different classes of central-station load. Fig. 39 illustrates the general idea graphically. It shows typical power and lighting-load graphs for an average city and also indicates the total-load graph which is obtained by adding together those for the power and the lighting loads. It will be noted that the power-load peak and the lighting-load peak do not occur at the same time. In other words, the maximum demand of the power load occurs at a different time from that of the lighting load. There is a diversity between their maximum demands.

It follows that the maximum demand on a transformer is less than the sum of the maximum demands of the consumers served from that transformer.

Also, the maximum demand imposed on a feeder is less than the sum of the maximum demands of the transformers fed from the feeder and the maximum demand on the generating station is less than the sum of the maximum demands of the feeders supplied from the station.

68. A Graphic Illustration of Diversity of Demand is given in Fig. 40 which was constructed from data obtained from a study of diversity.* For the purpose of this study 82 consumers were classed into 11 groups. The maximum demand of each of the 11 groups occurring during a certain year, was ascertained with maximum demand meters. The total area of each of the rectangles, 1 to 11, in the diagram, is proportional to the maximum demand of the corresponding group of consumers. Then the combined—or simultaneous—maximum demand during the same year for all of the 82 consumers was found. The combined maximum demand for all of the 82 consumers was 9,770 kw. and it occurred about 5:00 P.M. in December. At the same hour at which this 9,770 kw. was imposed on the central station, the maximum demands of the different groups were proportional to the shaded areas in the small rectanges. It will be noted that consumers of certain classes—such as the brick yards, quarries, ice manufacturers and cement works—imposed practically no demand on the system at the time (5:00 P.M. in December) when the aggregate demand of all of the 82 consumers was a maximum—9,770 kw.

69. The Importance of the Concept of Diversity of Demand can be appreciated if one considers the increase in generating and distributing—plant capacity that would be necessary if the maximum demands of all consumers occurred simultaneously. This matter of diversity is, therefore, of great economic significance. It is also of concern to the engineer—because a designer should consider it in planning his generating and substations and his distribution plant. Diversity is an element in the determination of rates for electric service. If it were not for the fact that the combined maximum demand imposed on

* Discussed by Samuel Insull in a paper "CENTRALIZATION OF ENERGY SUPPLY," delivered before the Finance Forum of the New York Y. M. C. A., on April 20, 1914.

an average central station is usually considerable less than half of the sum of the maximum demands of all of the consumers" the investment involved to provide electric service would be very much greater than that which is now required. If it were necessary to thus increase the investment, the cost of service would have to be increased accordingly.

70. The Diversity Factor of a System may be defined* as "the ratio of the sum of the maximum power demands of the sub-division of any system or parts of a system to the maximum demand of the whole system or of part of the system under consideration measured at the point of supply." In other words, a diversity factor is the ratio of the sum of the individual maximum demands of a number of loads during a specified period to the simultaneous maximum demand of all these same loads during the same period. If all of the loads in a group impose their maximum demands at the same time then the diversity factor of that group will be one (1).

EXAMPLE.—Consider two consumers each of which has a maximum demand for 100 kw. The sum of their individual maximum demands would then be 200 kw., but if a maximum demand meter in the circuit supplying these two consumers indicated only 150 kw.—as it might if the individual demands of the two consumers did not occur at the same time —the diversity factor between these two consumers would then be: 200 *kw.* ÷ 150 *kw.* = 1.33.

It follows then that:

$$(10)\ \textit{Diversity factor} = \frac{\textit{sum of individual max. demands}}{\textit{maximum demand of entire group}}.$$

$$(11)\ \textit{Sum of ind. max. dem.} = (\textit{diversity factor}) \times (\textit{max. dem. of entire group}).$$

$$(12)\ \textit{Max dem. of entire group} = \frac{\textit{sum of ind. max. dmds}}{\textit{diversity factor}}.$$

NOTE.—A diversity factor is sometimes given as the reciprocal of the value obtained from the above equations. That is, in such cases it is taken that: *Diversity factor* = (*max. dem. of entire group*) ÷ (*sum of ind. demands*). The factor thus obtained will, in every case, be equal to unity (one) or less. Such a factor is, usually, more convenient of application than is one derived by using equation (10). However, equation

*A. I. E. E. STANDARDIZATION RULES, Sec. 60.

(10) is in accord with the A. I. E. E. STANDARDIZATION RULE, Sec. 60, hence, is utilized herein.

EXAMPLE.—In Fig. 41, the sum of the individual maximum demands of the six component loads, as observed from the maximum-demand meters, M_1M_2, etc., is: $612 + 420 + 516 + 310 + 118 + 625 = 2{,}601$ *watts* $= 2.601$ *kw.* The maximum demand of the whole group as indicated on the maximum-demand indicator M_T, is only 0.86 kw. because the maximum demands of the consumers did not all occur at the same time. Then:

$$\textit{Diversity factor} = \frac{\textit{sum of ind. max. dem.}}{\textit{max. dem. of entire group}} = \frac{2.601}{0.86} = 3.02.$$

Therefore, the diversity factor between the six consumers of Fig. 41 and the supply main AB is 3.02.

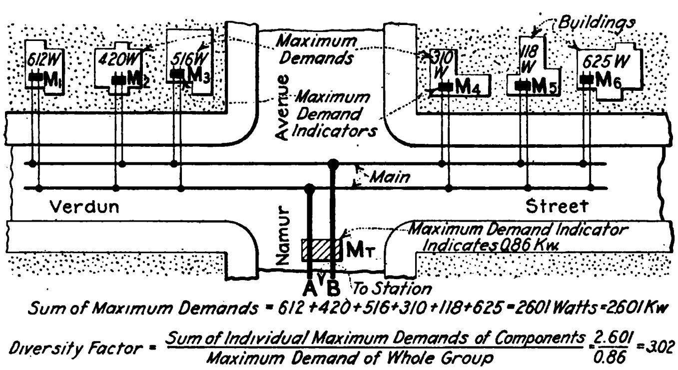


FIG. 41.—Illustrating the meaning and computation of diversity factor.

EXAMPLE.—The maximum demand of the power load A (Fig. 39), during the typical 24-hr. period shown, is 290 kw. The maximum demand of the lighting load B, is about the same, or 270 kw. But the maximum demand of the combined loads is, as shown at C, about 420 kw. What is the diversity factor for these loads? SOLUTION.—Substitute in equation (10): *div. fac.* = (*sum of ind. max. dem.*) ÷ (*max. dem. of entire group*) $= (290 + 270) \div 420 = 560 \div 420 = 1.33$. Hence, the diversity factor in this case is 1.33.

ILLUSTRATIVE EXAMPLE.—In Fig. 42 is diagrammed an imaginary case where four consumers 1, 2, 3, and 4 are supplied with electric service from the primary main AB through four transformers. The load graph for each of these four consumers is shown in Fig. 43, from which it is evident that their maximum demands are respectively 375, 425, 450 and 400 kw.; the maximum-demand indicators M_1, M_2, M_3 and M_4 would respectively indicate these individual maximum demands.

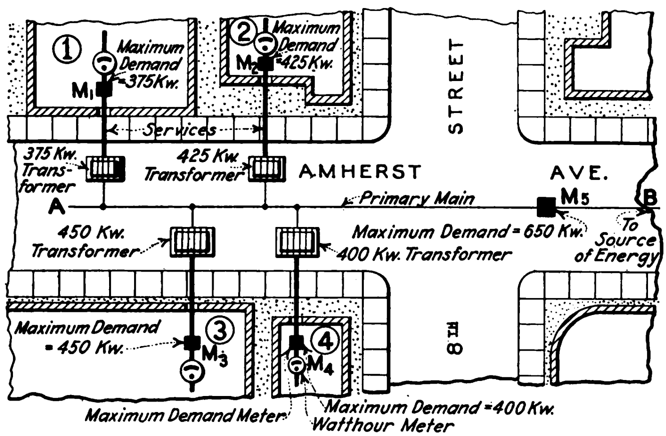


FIG. 42.—Lay-out of the loads, graphs of which are given in 1, 2, 3 and 4 of Fig. 43.

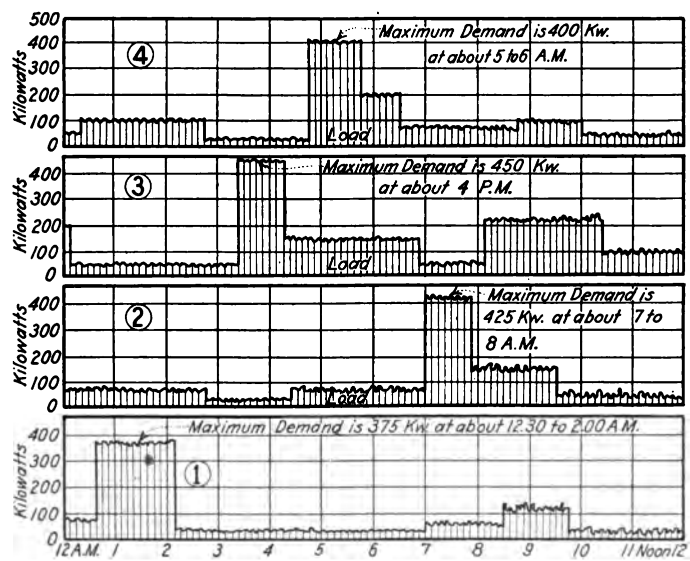


FIG. 43.—Graphs indicating the demands of four different imaginary loads.

From Fig. 44, in which are graphically added the graphs of 1, 2, 3 and 4, it is evident that, because of the diversity between the individual demands, the maximum demand of the entire group is only 650 kw. If a maximum-demand indicator, M_5 (Fig. 42), were inserted in the primary main it would, for the period under consideration, read 650 kw. It follows then that the diversity factor between these four consumers would from equation (10) be:

$$Div.\ fac. = \frac{sum\ of\ ind.\ max.\ dem.}{max.\ dem.\ of\ entire\ group} = \frac{375 + 425 + 450 + 400}{650} = 2.54.$$

NOTE that while the transformers to serve the four loads shown would have to be about of the capacities indicated in Fig. 42 to prevent overloading, the group of consumers would impose a maximum demand of only 650 kw. of the source of energy.

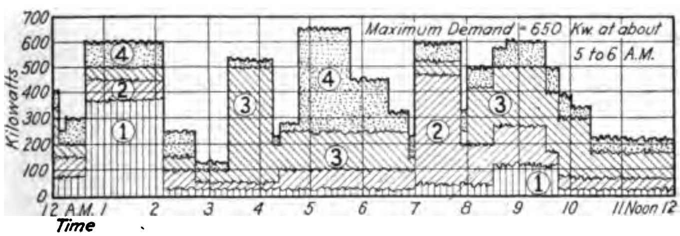
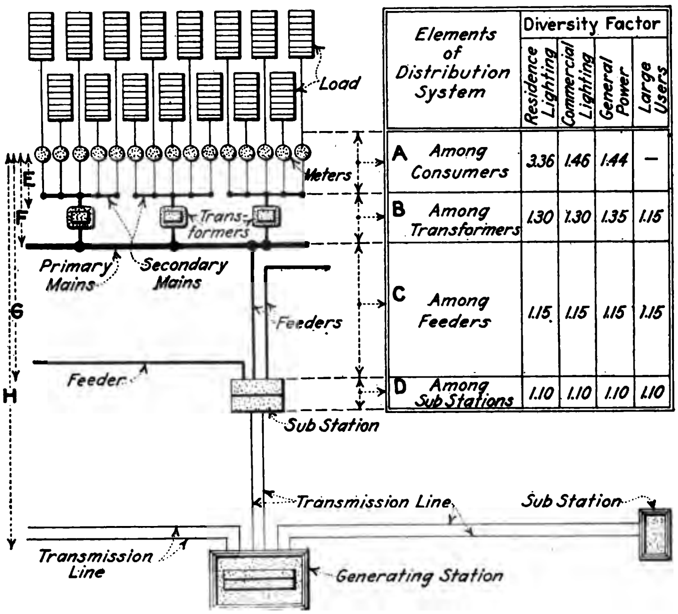


FIG. 44.—Graph of combined loads 1, 2, 3 and 4.

71. To Determine Diversity Factors it is necessary to take readings of the maximum demands on the different components of the systems under consideration. For most accurate results it is necessary to use maximum-demand indicators, which usually means that the service conductors of each consumer involved in the study must be equipped with a maximum-demand meter. Frequently maximum-demand meters are used on the consumers services in studies of this sort. Then, to obtain the equivalent watts demand, the maximum ampere demand imposed is multiplied by the normal voltage of the circuit, it being assumed that this voltage remains constant. H. B. Gear of the Chicago Edison Company has made important studies of diversity, some of which are outlined in detail in his book ELECTRIC CENTRAL STATION SYSTEMS. Most of the demand-factor values recited herein are based on his observations.

72. There May be Several Different Diversity Factors Applying to the Components of a Generation and Distribution System as illustrated in Fig. 45 and in Table 74. Thus, there may be a factor indicating:

1. The diversity among the demands of the different consumers.



Elements of Distribution System	Diversity Factor: Residence Lighting	Commercial Lighting	General Power	Large Users
A Among Consumers	3.36	1.46	1.44	—
B Among Transformers	1.30	1.30	1.35	1.15
C Among Feeders	1.15	1.15	1.15	1.15
D Among Sub Stations	1.10	1.10	1.10	1.10

FIG. 45.—Illustrating diversity of demand among different components of a distribution system.

2. The diversity among the demands of the transformers in a group.

3. The diversity among the demands imposed by the different feeders on a sub-station.

4. The diversity among the demands imposed by the different sub-stations on the generating station which serves them.

5. The diversity among the demands of the different classes of consumers—as diagrammed in Fig. 40.

73. Diversity-factor Values Are in a Measure Determined by Local Conditions.—The characteristics and habits of the people in a community will affect the values of the diversity factors applying to it. For a rural city the diversity factors will be somewhat different from those for a metropolis. The factors for a Southern town will be somewhat different from those for one in the North. Where the power load preponderates over the lighting, the overall diversity factor will be different from that where the opposite condition holds. Furthermore, the values of the diversity factors between certain of the components of a system may be determined in a measure by the layout of the system itself, as explained in a following paragraph under residence-lighting transformers. Hence, it is obvious that it is practically impossible to predict with accuracy the diversity factor that will apply for a given set of conditions unless one is already familiar with the diversity factor which has been ascertained by observation and test for like conditions. However, the factors which are suggested below and given in Table 75 are, probably, fairly typical. They may ordinarily be used without great error in estimating situations similar to those to which they apply specifically.

74. The Diversity of Demand Between Residence-lighting Consumers is usually, where a dozen or so consumers are involved, represented by a factor of about 3.4. In one block in Chicago, which was supplied by a single transformer and in which there were 34 consumers it was found* that the sum of the consumer's maximum demands was 12 kw., while the maximum demand of the group was 3.6 kw. This gave a diversity factor of: $12 \div 3.6 = 3.33$. In another block, where there were 185 consumers, the total of the individual consumers' maximum demands was 68 kw. The maximum demand imposed on the transformer serving the block was 20 kw. Hence, the diversity among these consumers was: $68 \div 20 = 3.40$. The factor indicating the diversity between the demands of residence consumers is quite large because a residence may be drawing a considerable load one evening and none at all the next. Furthermore, if one

* H. B. Gear.

residence in a group, possibly because of some social function, is imposing a relatively large demand, other residences in the same group, may, because of the same occasion, be taking but little power. For these reasons the diversity factor among residences is much greater than that among general power consumers. See also the values given in Fig. 45 and Table 75.

75. Diversity Factors for a Central-station Distributing System.—These data* are based on observations made in Chicago. (The reference letters *A*, *B*, *C*, etc., in the first column refer to Fig. 45.)

Elements of distribution system	Diversity factors			
	Residence lighting	Commercial lighting	General power	Large users
A Among consumers	3.36	1.46	1.44	....
B Among transformers	1.30	1.30	1.35	1.15
C Among feeders	1.15	1.15	1.15	1.15
D Among sub-stations	1.10	1.10	1.10	1.10
E Consumer to transformer	3.36	1.46	1.44	....
F Consumer to feeder	4.35	1.91	1.95	1.15
G Consumer to sub-station	5.00	2.19	2.24	1.32
H Consumer to generator	5.53	2.41	2.45	1.45

76. The Diversity Among the Demands of Commercial Lighting Consumers is not, experience shows, nearly so pronounced as with residences. The reason for this is that commercial lighting—in the factories and stores—is ordinarily used about the same hours in the day and about the same days in the week by one business concern as by another. The result is that the diversity factor between a number of these consumers is usually relatively low, possibly in the neighbor-

* See H. B. Gear in the STANDARD HANDBOOK.

hood of 1.4. That the factor is this large is because some commercial consumers, department stores for instance, use most of the light in the late afternoon or early in the evening, while other concerns, hotels for example, use most of their light in the evenings. See Fig. 40 and Table 75.

77. The Diversity Among Demands Imposed on the Mains by Lighting Transformers for residence and commercial service may, for well-designed distribution systems, be represented probably by an average factor of from 1.30 to 1.35. If a large number of small transformers are used to serve a load, instead of a few large ones, the resulting diversity factor

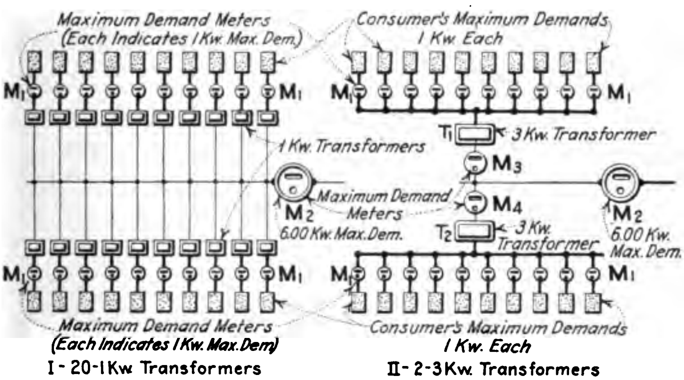


FIG. 46.—Showin how the diversity factor between transformers may differ with the arrangement of the transformers.

among the transformers will probably be greater than 1.30. The reason for this is that if a large number of small transformers are installed, the *sum* of the individual maximum demands imposed by a large number of small transformers will be greater than the sum of the individual demands imposed by a few large transformers serving the same load, the combined maximum demand of the group being the same in each case. The following example illustrates this principle.

EXAMPLE.—Consider the imaginary condition illustrated in Fig. 46, where there are 20 consumers, each having a maximum demand of 1 kw. as indicated by the maximum demand meters M_1. Assume that the maximum demand of the group of 20 consumers is 6 kw. as indicated by meters M_2. Then, if twenty 1-kw. transformers are used to serve

the load, as at *I*, the diversity factor between transformers is: 20 *kw.* ÷ 6 *kw.* = 3.33.

Assume that these 20 customers are to be served by only two transformers each feeding 10 consumers as at *II*. Also assume that the same diversity factor, 3.33, would obtain between consumers. Then the maximum demand imposed by transformers I_1 and I_2 would each be: 10 *kw.* ÷ 3.33 = 3 *kw.* The sum of their maximum demands would be: 3 + 3 = 6 *kw.* Hence, the diversity factor between these two transformers would be: 6 *kw.* ÷ 6 *kw.* = 1.00. These conditions are, obviously, imaginary but the example indicates how diversity is determined to some extent by the arrangement and capacities of the component equipment.

NOTE that in the example just given, the economy in transformer capacity resulting from the grouping of a relatively large number of consumers on one transformer. In Case *I* twenty 1-kw. transformers are required while in Case *II*, two 3-kw. transformers will handle the load.

The average diversity factor among residence-lighting transformers in a number of Minnesota cities is 1.60.* This rather high value is attributed to the fact that probably an unnecessary large number of small transformers were used.

NOTE.—If the sum of the individual maximum demands of a group of transformers be divided by the diversity factor among transformers, for the condition under consideration, the resulting value will be the maximum demand which the group imposes on the feeder or line serving it. The examples which follow illustrate this proposition.

78. To Determine the Maximum Demand That Will be Imposed on Any Transformer, Feeder or Station, when the connected load, demand and diversity factors are known: *Multiply the connected load by the demand factor and divide the product by the diversity factor.* That is:

$$(13)\quad Max.\ dem.\ of\ entire\ group = \frac{(conn.\ load) \times (dem.\ fact.)}{diversity\ factor}.$$

The following actual example recited by P. J. Nilsen† illustrates a practical utilization of this rule, and indicates the economics which may be effected through its application.

ILLUSTRATIVE EXAMPLE.—The utility operated in a town of 800 inhabitants. Energy was purchased at 13,200 volts for 6.5 cts. per

* W. T. Ryan.

† *Electrical Review,* Aug. 5, 1916, p. 230.

kw.-hr. A 50-kva. outdoor-transformer sub-station reduces the voltage to 2,300 for distribution to the lighting load detailed below in Table *A*. Before the hereinafter-described changes in transformer capacities were effected the distribution energy losses (energy lost and unaccounted for) were equal to one-half the energy sold; the distribution-loss factor was 50 per cent.

It is evident from a consideration of following Table *A* that the original transformer capacity was much too large. The sub-station transformer capacity (50 kva.) was twice as great as the total distribution transformer and larger than the connected load.

TABLE A.—CONNECTED LOADS AND THE TRANSFORMER CAPACITIES ORIGINALLY EMPLOYED TO SERVE THEM

Transformer number...	1	2	3	4	5	Total
Rating in kva.........	5	10	3	3	5	26
Connected-load kva.						
Residences...........	6.48	9.92	6.17	10.15	0	32.72
Stores..............	6.00	0	5.50	0	0	11.50
Streets.............	0	0	0	0	4.80	4.80
Total............	12.48	9.92	11.67	10.15	4.80	49.02

For a 53-day period during the winter the energy purchased was 2,500 kw.-hr., while the energy sold was only 1,600 kw.-hr., which left 900 kw.-hr. unaccounted for. Simple calculations disclosed that the sum of the transformer-core losses and of the meter potential-coil losses for the 53-day period totaled 738 kw.-hr. Only 162 kw.-hr. then remained unaccounted for. This was probably due to losses in the transmission and distribution line wires which losses were not estimated.

By applying the demand and diversity factors specified in Table *B* to the connected-load values of Table *A* the logical "proposed" transformer capacities given in column *IV*, Table *C* were computed. Thus, considering only *the maximum demand imposed by the residence-lighting load* (Table *A*) on transformer No. 1 and substituting in equation (13):

$$\textit{Max. dem. of entire group} = \frac{(\textit{con. load}) \times (\textit{dem. fac.})}{\textit{diversity factor}} = \frac{6.48 \times 0.45}{3.57} = 0.817 \textit{ kva.}$$

Then, for *the store-lighting load*:

$$\textit{Max. dem. of entire group} = \frac{(\textit{con. load}) \times (\textit{dem. fac.})}{\textit{diversity factor}} = \frac{6.00 \times 0.75}{1.54} = 2.92 \textit{ kva.}$$

But since there is a diversity between the demands of store and residence-lighting loads, the maximum demand imposed by these two loads on the transformer which serves them would be:

$$\textit{Max. dem. of entire group} = \frac{\textit{sum of ind. max. dem.}}{\textit{diversity factor}} = \frac{0.817 + 2.92}{1.18} = 3.16 \; \textit{kva.}$$

Hence, the estimated maximum demand imposed on transformer No. 1 would be 3.16 kva. (column *II*) and obviously a 3-kva. (column *IV*) transformer would be of ample capacity to handle this load. The other "Simultaneous Maximum Demands" given in column *III* of Table *C* were computed by a process similar to that above outlined.

To obtain the maximum demand imposed on the sub-station transformer, the sum of the individual maximum demands of all of the distributing transformers (column *II*, of Table *C*) should be divided by the diversity factor between these transformers and the sub-station (Table *B*) thus:

TABLE *B*.—DEMAND AND DIVERSITY FACTORS EMPLOYED

The diversity factors indicated below are probably somewhat larger than those ordinarily employed under similar conditions. However, their use is probably justified in this instance inasmuch as McNilsen advises that the average winter month consumption per consumer in this town was only 5.83 kw.-hr.

Designation of factors	Factors		
	Residences		Stores
Consumers' demand factor......	0.55	.....	0.75
Group diversity factor:			
Consumer to transformer......	3.57	.....	1.54
Between stores and residences..	.....	1.18	.....
Transformers to substation....	.....	1.33	.....

TABLE C.—SHOWING ESTIMATED, SIMULTANEOUS MAXIMUM DEMANDS, NEW TRANSFORMER CAPACITIES BASED THEREON AND SAVINGS RESULTING THROUGH THE USE OF THESE NEW CAPACITIES

I Transformer number	II Simultaneous demand, kva.	III Rating present, kva.	IV Proposed kva.	V Yearly saving in core losses	VI Saving in investment
1	3.16	5	3.0	$5.12 or 21 per cent.	$27.00 or 44 per cent.
2	1.25	10	7.5*	$6.27 or 16 per cent.	$12.25 or 16 per cent.
3	3.03	3	3.0	None	None
4	1.28	3	1.5	$6.27 or 32 per cent.	$10.20 or 29 per cent.
5	4.80	5	5.0	None	None
Sub-station...	11.36	50	15.0	$81.10 or 70 per cent.	$165.68 or 61 per cent.
Total.........	.....	76	35.0	$98.76 or 42 per cent.	$215.13 or 40 per cent.

* A 7.5-kw. transformer provided here to take care of a possible 7.5-h.p. day load. Not necessary to provide for future growth.

$$Max.\ dem.\ of\ entire\ group = \frac{sum\ of\ ind.\ max.\ dem.}{diversity\ factor}$$

$$= \frac{3.16 + 1.25 + 3.03 + 1.28}{1.33} = 6.56\ kva.$$

Therefore, the simultaneous maximum demand imposed on the sub-station transformer would be: 6.56 + 4.8 = 11.36 *kva.* (column *II*, Table *C*) and a 15-kva. transformer (column *IV*, *D*) would be of ample capacity to carry the entire load and provide for some growth.

It is evident from Table *A* that the changes resulted in a decrease in aggregate transformer rating from 76 to 35 kw. or 54 per cent. This represents a saving of approximately 40 per cent. in transformer investment. The change also resulted in a decrease of about 42 per cent. in core losses or, at 6.5 cts. per kw.-hr., $98.76 per year operating expense. The sub-station transformer core loss could be further reduced by using a 10-kw. transformer from April 1 to Oct. 1, and then installing an additional 5-kw. unit for the winter load. However, the increase in investment and attendance cost involved, would offset the saving in core loss.

EXAMPLE.—Consider the conditions of Fig. 47, wherein 36 residence-lighting consumers are shown. The connected load of each consumer in

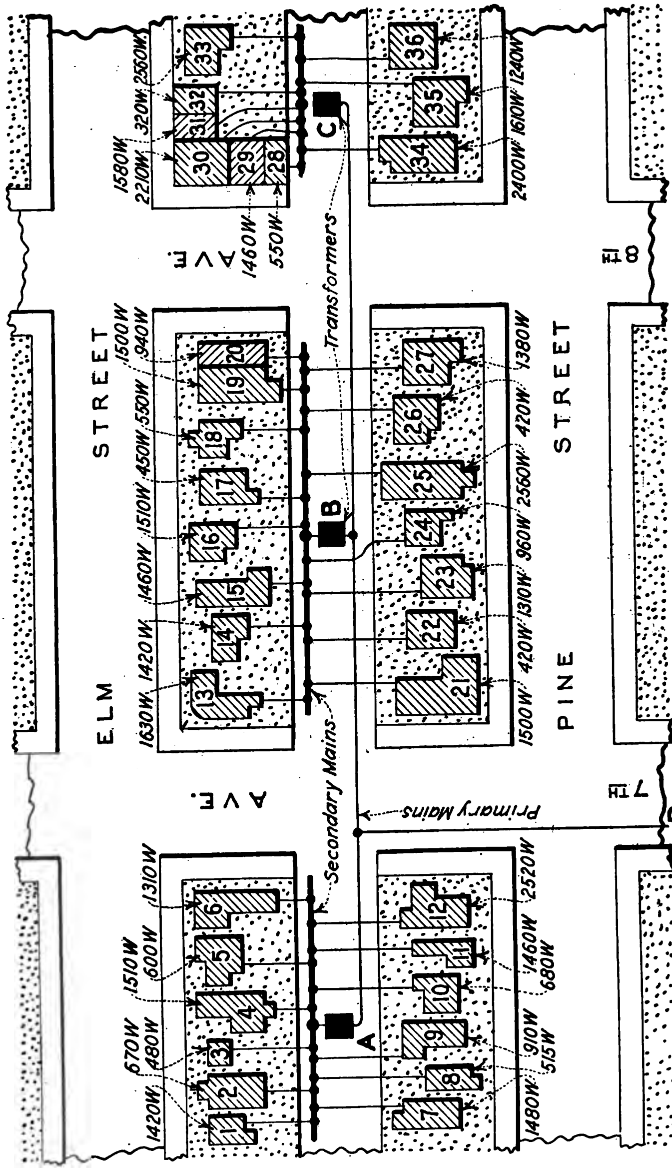


FIG. 47.—A group of thirty-six residences served by three transformers.

watts is indicated at each building. If it is decided to serve these consumers with three transformers, A, B and C, what should the capacities of these transformers be and what will be the maximum demand imposed on the primary main at D? It will be assumed that the consumers demand factor is 0.50, that the diversity factor among these consumers is 3.35 and that the diversity factor among transformers is 1.3. SOLUTION. —The connected load of Group A is: $1{,}420 + 670 + 480 + 1{,}510 + 600 + 1{,}310 + 1{,}480 + 515 + 910 + 680 + 1{,}460 + 2{,}520 = 13{,}555$ *watts* = 13.6 *kw*. Then substituting in equation (13):

$$\textit{Max. dem. of entire group} = \frac{(\textit{con. ld.}) \times (\textit{dem. fac.})}{\textit{diversity factor}} = \frac{13.6 \times 0.5}{3.35} = 2.00 \; kw.$$

Therefore, a 2-kva. transformer could be used at A.

The connected load of Group B is: $1{,}630 + 1{,}420 + 1{,}460 + 1{,}510 + 450 + 550 + 11{,}500 + 940 + 1{,}500 + 420 + 1{,}310 + 960 + 2{,}560 + 420 + 1{,}380 = 18{,}010$ *watts* = 18 *kw*. Then substituting in equation (13):

$$\textit{Max. dem. of ent. group} = \frac{(\textit{con. ld.}) \times (\textit{dem. fac.})}{\textit{diversity factor}} = \frac{18 \times 0.5}{3.35} = 2.7 \; kw.$$

Therefore, a 3-kva. transformer could be used at B.

The connected load of group C is: $550 + 1{,}460 + 2{,}210 + 1{,}580 + 320 + 2{,}560 + 2{,}400 + 1{,}610 + 1{,}240 = 13{,}930$ *watts* = 13.9 *kw*. Then substituting in equation (13):

$$\textit{Max. dem. of entire group} = \frac{(\textit{con. ld.}) \times (\textit{dem. fac.})}{\textit{diversity factor}} = \frac{13.9 \times 0.5}{3.35} = 2.1 \; kw.$$

Therefore, a 2-kva. transformer would probably suffice at C.

Now to find the maximum demand imposed on primary main D substitute in equation (13):

$$\textit{Max. dem. of entire group} = \frac{2.0 + 2.7 + 2.1}{1.3} = \frac{6.8}{1.3} = 5.2 \; kw.$$

Therefore, 5.2 kw. would be the maximum demand on the primary main at D. In actual practice it would, probably, be desirable to serve all the consumers shown in Fig. 47 by installing one or two larger transformers, instead of using three relatively small ones as shown. However, the example illustrates the principle involved.

Note.—To Utilize the Principle of Diversity of Demand Between Lighting Consumers Most Effectively, that is, to insure a maximum diversity factor, there should usually be a minimum of from 8 to 12 consumers served from each distributing transformer.

78A. The Diversity of the Demands Among Feeders appears to range in the neighborhood of about 1.15 in a well-designed system. In other words, the maximum demands on feeders usually occur almost simultaneously.

Example.—If a generating station serves two feeders, one of which imposes a maximum demand of 650 kw. and the other a maximum demand of 485 kw., what will be the maximum demand which the two will impose on the station, it being assumed that the diversity factor for these feeders is 1.15. Solution.—

$$\textit{Max. dem. of entire group} = \frac{\textit{sum of ind. max. dem.}}{\textit{diversity factor}}$$
$$= \frac{650 + 485}{1.15} = \frac{1,135}{1.15} = 988\ kw.$$

Therefore, the maximum demand which these two feeders would impose on the station would be 988 kw.

79. There Is a Diversity Among the Demands of Different Sub-stations where such form a part of a distribution system. The value of the factor representing this diversity will obviously be determined by the characteristics of the territory served by the sub-station. If one sub-station serves a residence district and another a factory district the diversity factor is liable to be large. On the other hand, the diversity factor between the demands of two sub-stations, both serving manufacturing communities—or any two communities of similar characteristics—is liable to be small, that is, in the neighborhood of 1.00.

80. The Total Diversity Factor for a System is equal to the product of the diversity factors of all of the components of the system.

Example.—What is the total diversity factor for the residence-lighting load of a system where the component diversity factors are (see Table 74) as follows: Among consumers, 3.36; among transformers, 1.30; among feeders, 1.15; among substations, 1.11? Solution.—The product of these factors is $3.36 \times 1.30 \times 1.15 \times 1.11 = 5.53$. That is,

5.53 is the total diversity factor (note this value in the second column of Table 75) by which the sum of the individual maximum demands of lighting consumers should be multiplied to obtain the maximum demand that would probably be imposed by them on the generating equipment. The total diversity factor in the Chicago system for the lighting and power load, but not including electric railways, is 3.2 during the winter months.*

81. To Determine the Kilowatt Station Capacity Required per 100 Kw. Connected Loads.—*Divide the consumer's demand factor expressed as a percentage by the total diversity factor.*

EXAMPLE.—If the total diversity factor for a residence-lighting load is 5.53 (see above paragraph) and the demand factor is 75 per cent., what kilowatt station capacity will be required per 100 kw. of lighting load? SOLUTION.—75 ÷ 5.53 = 13.6. Hence, about 13.6-kw. station capacity would be required, under these conditions, per 100 kw. connected residence-lighting load.

NOTE.—By the above outlined process it can be shown that, for commercial-lighting loads, about 37-kw. station capacity is necessary per 100 kw. connected and for general power loads about 40 kw. per 100 kw. connected. In Minneapolis† (population 325,000) the ratio of the maximum demand imposed on the station to the total connected load is approximately 1 to 3, that is, 33-kw. station capacity per 100 kw. connected load.

82. One Hundred Per Cent. Minus the Reciprocal of the Diversity Factor in Per Cent. Gives the Percentage of Apparatus Which May Be Eliminated by Grouping Consumers for Elements of a System Onto One Supply Source.—The following examples amplify this statement:

EXAMPLE.—Consider three individual loads having maximum demands of 100, 300, 200 and 600 kw. respectively. If each of these loads was to be served by a separate transformer or station the aggregate apparatus capacity required would be: 100 + 300 + 200 + 600 = 1,200 *kw.* However, assume that the diversity factor between these loads is 3.00. Then the maximum demand of the group would be only: 1,200 ÷ 3.0 = 400 *kw.* and 400 kw. of equipment would serve the combined loads. The saving in required apparatus would then be: 1,200 − 400 = 800 *kw.* That is, the saving would be: 800 ÷ 1,200 = 66.7 *per cent.* Now also the reciprocal of the diversity factor in this case is: 1 ÷ 3 = 0.333 = 33.3 *per cent.* And 100 *per cent.* − 33.3 *per cent.* = 66.7 *per cent.*, which verifies the proposition heading this paragraph.

* H. B. Gear.
† W. T. Ryan.

EXAMPLE.—The yearly diversity* between the maximum demands of lighting-and-power and electric-street-and elevated-railway loads in Chicago for 1911 and 1912 permits, by combining the generating apparatus, a saving in apparatus of 8.1 per cent. Then the reciprocal of the diversity factor would be 100 *per cent.* − 8.1 *per cent.* = 91.9 *per cent.*, that is 0.919. The diversity factor would then be 1 ÷ 0.919 = 1.09.

83. The Importance of Diversity as a Factor in Plant Design can readily be appreciated from a consideration of the preceding information. A distributing or generating plant must be designed largely on the basis of the maximum demand that will be imposed on it. Therefore, if the designer of a new installation is familiar with the diversity factors that are liable to obtain for the conditions under which his system will operate he can readily determine the required capacities for the members of the system by applying suitable demand and diversity values. As hereinbefore suggested, diversity of demand is of importance in the establishment of rates for central-station service. It is a fact that in many cases the capacity of a generating station, hence, the investment, is largely determined by the peak lighting load in the evening. The station apparatus must be large enough to handle this lighting load. However, during the day a considerable portion of the station equipment required to serve this lighting load is utilized for supplying the power load. Obviously, if the maximum demands of the power and lighting loads were coincident the station capacity and investment would have to be much greater than is now actually necessary.

NOTE.—Considering the situation in this light, the energy thus supplied for power during the day time is somewhat of the nature of a by-product and can, therefore, be sold at a correspondingly lower rate than can energy for lighting service.

* Samuel Insull in the STANDARD HANDBOOK.

SECTION 5

LOAD FACTOR, PLANT FACTOR AND CONNECTED-LOAD FACTOR

84. The Load Factor of a Machine, Plant or System is* "*the ratio of the average power to the maximum power during a certain period of time.* The average power is taken over a certain period of time such as a day, a month or a year and the maximum power is taken as the average over a short interval of the maximum load within that period. In each case, the interval of maximum load and the period over which the average power is taken should be definitely specified, such as 'half-hour monthly' load factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used."

85. Load Factors Are Expressed as Percentages.—The "average power" may be either that generated or consumed, depending on whether the equipment under consideration is, respectively (1) *generating or delivering*, or (2) *receiving or consuming equipment.* The "maximum power averaged over a short interval" is the maximum demand.

NOTE.—The term "half-hour monthly load factor" used in Art. 84 means that the maximum demand is based on a half-hour time interval and the power load is averaged over a month.

86. The Formulas for Load Factor may (if the term "*maximum demand*," which is really implied, be substituted for "maximum power" in the definition in Art. 84) be written thus:

$$\text{(14)} \qquad \textit{Load factor} = \frac{\textit{average power}}{\textit{maximum demand}}$$

$$\text{(15)} \qquad \textit{Average power} = (\textit{load factor}) \times (\textit{maximum demand})$$

$$\text{(16)} \qquad \textit{Maximum demand} = \frac{\textit{average power}}{\textit{load factor.}}$$

* A. I. E. E. STANDARDIZATION RULES, revised June 28, 1916, Sec. 55.

Example.—In the central station serving a certain city of 8,000 inhabitants the peak load or 30-min.-interval maximum demand for the year 1915 was 580 kw. and the average power 232 kw. What was the 30-min., annual load factor for that year? Solution.—Substituting in the above formula (14) *load factor* = (*average power*) ÷ (*maximum demand*) = 232 ÷ 580 = 0.40 = 40 *per cent.* Hence, the 30-min. annual load factor for this station was 40 per cent. for the year 1915. Figs. 48 and 49 show other examples.

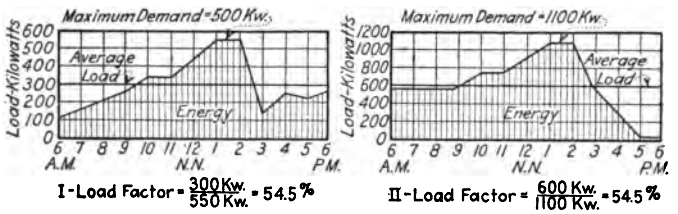


Fig. 48.—Two graphs of twelve-hour loads the load factor of each of which is 54.5 per cent.

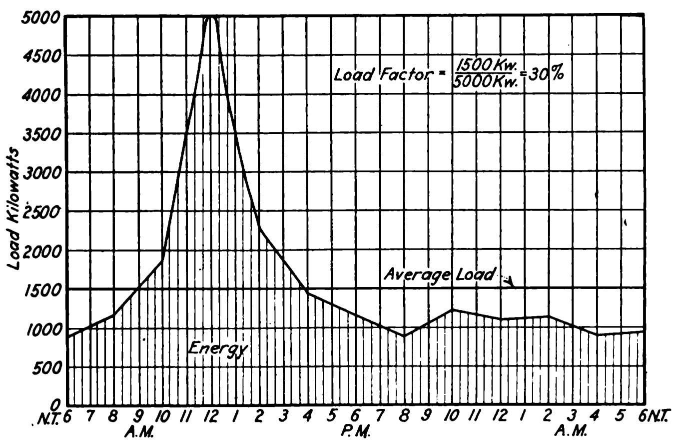


Fig. 49.—Load graph for an average twenty-four hour working day. Load factor is 30 per cent.

87. The Real Significance of a Load Factor is this: It affords an index as to the proportion of the whole time that the machine, plant or system to which it applies is being worked at its full capacity. The machine, plant or system must be so selected or designed that it will handle the maximum power demand that will be imposed on it. But it is seldom, because

of the general nature of things, that any equipment will have the maximum demand which it can handle imposed on it during all of the 8,760 hr. of a year.

But whether the equipment is unloaded or fully loaded there are certain fixed charges (interest, depreciation, taxes, insurance, standby costs, and the like) which are adding up continually. That is, any equipment is costing its owner money whether it is producing or idle. Now during the hours that the equipment is well or fully loaded it is earning more money than it is spending, hence, nets a profit. The more nearly fully loaded it is the more money—net—it is earning. Hence, it follows from an economic standpoint that it is desirable to keep all equipment as near fully loaded as possible during all of the hours of each year—that is, it is desirable to obtain and maintain a high load factor. The graphs of Figs. 50 and 51, discussed in other articles, illustrate this principle.

EXAMPLE.—If a machine has imposed on it exactly the same power load during all of the 8,760 hr. of a year, then obviously the average power load is equal to the maximum demand and then the annual load factor for that year would be 100 per cent.

EXAMPLE.—If a machine has imposed on it 1,000 kw. half of the time and no load at all the other half of the time, then the average load will be 500 kw. The maximum load is 1,000 kw. Hence, the load factor is $500 \div 1{,}000 = 0.50 = 50$ *per cent.* A load factor of 50 per cent. then implies that the equipment to which it relates is producing to the extent of only half of its ability.

NOTE.—It is obvious then that *a load factor denotes the percentage of the whole time which the equipment is idle,* it being assumed that the equipment is just capable of handling the maximum demand. Load-factor values are used, principally, to determine the average power (or indirectly energy expenditure) of an installation when the maximum demand is known—or to obtain the maximum demand when the average power or energy consumption is known.

88. The Effect of Increased Diversity of Demand Is to Increase Load Factor almost in direct proportion to the increase of diversity factor. Thus, H. B. Gear states that, in Chicago, the load factor of residence consumers individually is only 7 per cent., while in groups it is about 23 per cent. The group load factor of commercial-lighting consumers is about 16 per cent. and for general power users is about 17 per cent. How-

ever, when these three classes of consumers are combined, the load factor of the load which they impose on the station is about 35 per cent. during the winter months.

89. The Effect of Load Factor on Central-station Rates is a feature that should be understood. As the load factor decreases, the cost of supplying energy must necessarily increase.

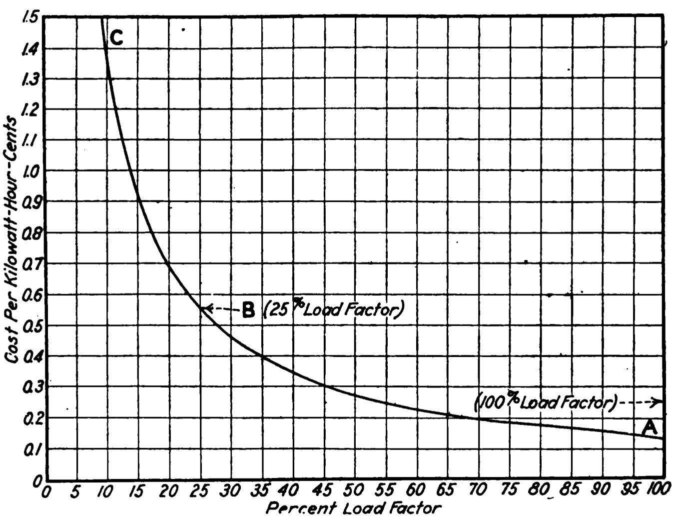


FIG. 50.—Graph illustrating the increase in fixed charges per kilowatt hour as the load factor increases. (Based on a plant of 100 kw. maximum load costing $10,000 with fixed charges at 12 per cent.)

A central station or utility plant must have sufficient capacity so that it can at any time supply the maximum demand of the system which it serves. Usually, the lighting load in the evening determines the maximum demand and, therefore, it is only for a few hours in the evening that the equipment is earning all the money which it is capable of earning. During certain "off-peak" hours the equipment may be relatively idle. Therefore, when "off-peak" loads can be obtained, they are somewhat in the nature of a by-product. But they tend to increase the total load factor of the system and thereby decrease the average cost per unit of energy. Hence, it is beneficial to all for the utility company to seek and accept such loads

at rates considerably lower than those which it is necessary to charge for service which may be coincident with the peak load or maximum demand on the supply station.

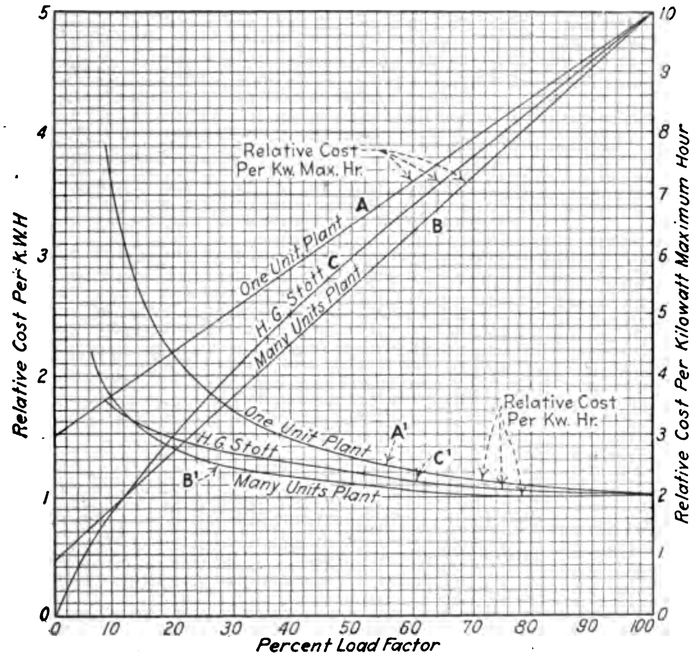


FIG. 51.—Graph (H. G. Stott) showing how the cost of generating energy increases as the load factor decreases. Graphs show only operating and maintenance costs.

The following examples illustrate the application of these graphs: Consider a generating plant operating several units at an annual load factor of 30 per cent. and making energy for 5 mills per kwh. What would be the cost per kwh. on a 60 per cent. load factor basis? Refer to graph C^1, then on the basis of Mr. Stott's experience: Relative cost per kwh. at 30 per cent. load factor = 1.35 relative cost per kwh. at 60 per cent. load factor = 1.13. Then, the expected cost at 60 per cent. load factor = (1.13 ÷ 1.35) × 5 = 4.2 *mills per kwh.*

Now to illustrate the application of graphs *A*, *B* or *C* which may be used for estimating costs on the basis of the *peak or maximum* power load: Consider the same plant of the above example; the total annual cost per kwh. of operating the plant at 30 per cent. load factor is: 8760 *hr.* × 5 *mills* = $43.80. But the annual cost per *peak or maximum kw, per year* = $43.80 × 0.30 = $13.14. Now referring to graph *C*: Relative cost per max. kw. per year at 30 per cent. load factor = 4.05. And, relative cost per max. kw. hr. per year at 60 per cent. load factor = 6.82. Then, the expected cost per kw. max. hour, per year at 60 per cent. load factor = (6.82 ÷ 4.05) × $13.14 = $22.10.

While the "*C*" graphs were used in the above examples, either the "*A*" or "*B*" graphs may be utilized in the same manner for conditions which justify their application.

NOTE.—Fixed charges vary inversely as the load factor (see example relating to Fig. 50). Operating cost* (Fig. 51) varies inversely about as the fourth root of the load factor.

* H. G. Stott.

90. The Period Over Which a Load Factor Should be Reckoned will be determined by the circumstances of the case. Where an ordinary load to be supplied by a central station is involved, it is usual to consider only an annual or 8,760-hr. load factor—which is discussed in detail in another article. Where no period is specified, an annual load factor is usually assumed. Since no-load costs in an electric generating station during any month or week are determined largely by the peak load expected during the month or week,* it is evident that load factors for a shorter period than a year should be used as a basis of power-plant-cost comparisons. Possibly the average daily—or weekly—load factor provides the best value for such comparisons.

91. To Compute the Average Power or the Energy Consumption Over a Given Period of Time the following formulas may be used. To calculate average power: *Divide the kilowatt-hours energy expended during the period by the number of hours in the period: the result will be the average power, in kilowatts, during the period.* That is:

$$(17) \quad \textit{Average power} = \frac{\textit{kw.-hr. expended during period}}{\textit{no. of hr. in period}}$$

and,

$$(18) \quad \textit{no. of hr. in period} = \frac{\textit{kw.-hr. expended during period}}{\textit{average power}}$$

also,

$$(19) \quad \textit{kw.-hr. expd. dur. period} = (\textit{av. power}) \times (\textit{no. hr. in period}).$$

EXAMPLE.—Refer to Fig. 52. What was the average load on Generator G_1 which operated 5,545 hr. during a year and developed 133,080 kw.-hr. of energy? SOLUTION.—Substitute in equation (17): *Av. power* = (*kw.-hr. expended during period*) ÷ (*no. of hr. in period*) = 133,080 ÷ 5,545 = 24 *kw.*

EXAMPLE.—Likewise, the average load on Generator G_2 was: 156,000 *kw.-hr.* ÷ 7,800 *hr.* = 20 *kw.*

EXAMPLE.—What was the average load for the year on the generating station diagrammed in Fig. 52, which, as indicated by watt-hour meter W_3, supplied 289,080 kw.-hr. of energy during the entire year of 8,760 hr.? SOLUTION.—Substituting in equation (17): *Av. power* = (*kw.-hr. ex-*

* G. I. Rhodes.

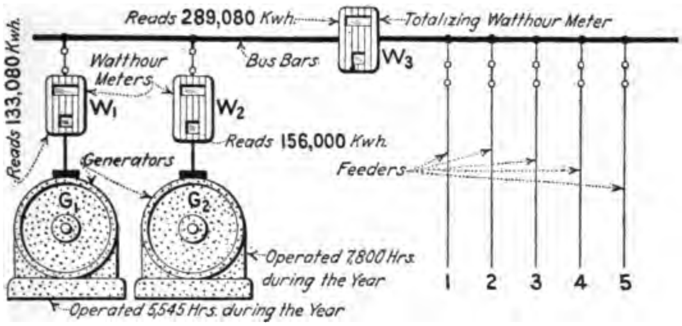


FIG. 52.—Examples in determing average loads.

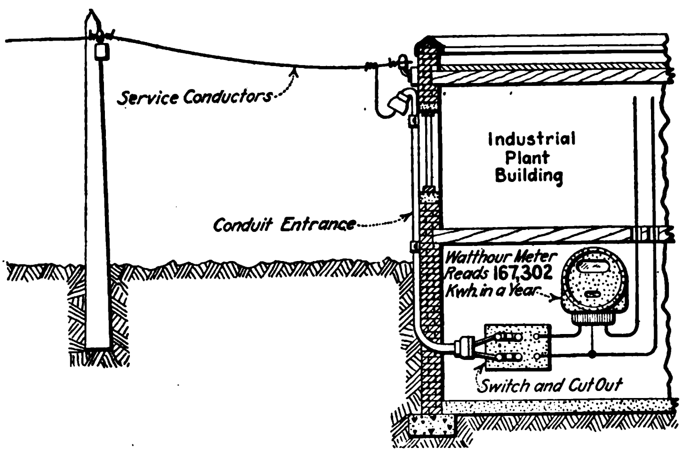


FIG. 53.—Determination of average load imposed by an industrial plant.

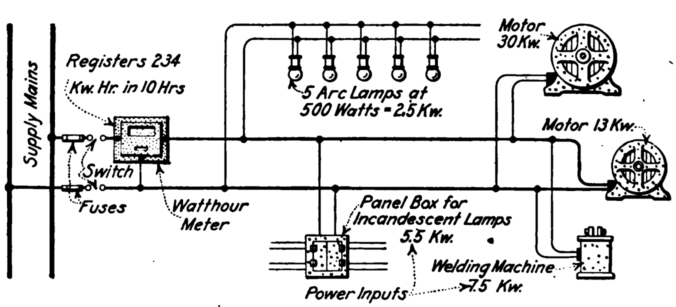


FIG. 54.—A capacity-factor problem.

pended during period) ÷ (*no. of hr. in period*) = 289,080 ÷ 8,760 = 33 *kw.* = average annual load.

EXAMPLE.—The watt-hour meter totaling the energy supplied to a certain industrial plant (Fig. 53) indicated during a certain year an annual consumption of 167,302 kw.-hr. What was the average load imposed by this plant during this year? SOLUTION.—Substituting in equation (17): *Av. power* = (*kw.-hr. expended during period*) ÷ (*no. of hr. in period*) = 167,302 ÷ 8,760 = 19.1 *kw.* That is, the average annual load imposed was 19.1 kw. Also see Fig. 54, for another example.

92. To Determine the Average Power From a Load Curve, either the graphic method illustrated in Fig. 55 and in the following example or that involving the use of a planimeter (Figs. 56, 57, 58 and 59) described below may be used. The general procedure is quite similar to that used in obtaining the mean effective pressure from a steam-engine indicator diagram.

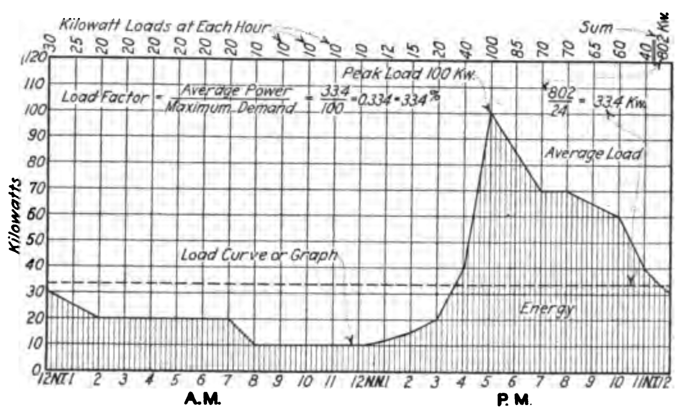


FIG. 55.—Illustrating method of computing maximum demand from a load graph.

93. The Rule for the Graphic Method of Finding the Average Power From a Load Curve is: *Scale or read from the load graph, the momentary power expenditures at the ends of suitable, equal time intervals over the entire time comprehended by the graph. Then add these momentary power-expenditure values together and divide their sum by the number of periods into which the entire time was apportioned. The result will be the average power expenditure or average load.*

The number of time intervals into which the entire time should be divided is determined by the contour of the graph and by the degree of accuracy desired. In general, the greater the number of intervals taken the more accurate will be the result. However, where the contour of the graph is quite regular and it comprehends 24 hr. of time, as in Fig. 55, the result will usually be sufficiently accurate for practical work if 1-hr. intervals are assumed. It is seldom necessary to use intervals smaller than half an hour on a graph comprehending a 24-hr. period. When the contour of the graph is extremely irregular and comprehends a short period of time, it may be desirable, to insure sufficiently accurate results, to use 15-min., 5 min. or even 1-min. intervals

Example.—What is the average power for the load graph shown in Fig. 55? Solution.—Since this curve (which is an imaginary one) is quite regular, the momentary power expenditures were taken at the end of each 1-hr. interval. These are given above the graph: 30, 25, 20, 20 kw., etc. The sum of all of these momentary demands is 802 kw. Since the graph was divided into 24 intervals, *average load* = 802 ÷ 24 = 33.4 *kw.*

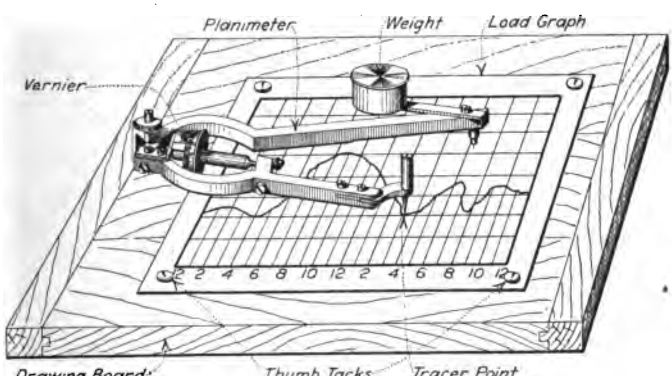


Fig. 56.—Finding the average load from a load graph with a planimeter.

94. In Determining the Average Power From a Load Graph With an Ordinary Polar Planimeter (Figs. 56 and 57) *ascertain the actual area of the portion within the graph—which represents energy or kilowatt-hour—in square inches by using the planimeter. Now divide this area by the actual length of*

the graph in inches. The quotient thus obtained will be the average height or length or ordinate of the graph, in inches. Then find by scaling along the ordinate axis of the graph the kilowatt equivalent of this average height. This kilowatt equivalent will be the average power in kilowatts.

If the planimeter which is being used is not sufficiently large to indicate the area of the graph under consideration in one sweep, divide the total area, with vertical pencil lines, into three or four sections, which need not be equal; find the area

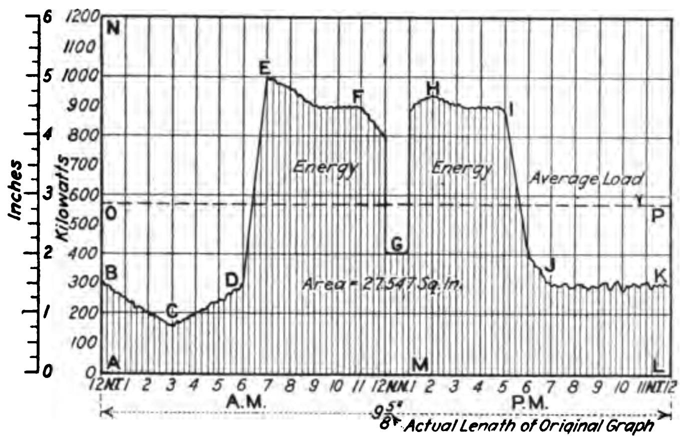


FIG. 57.—Example of the determination of average load using a planimeter.

of each section and then add all of these partial areas together to obtain the total area. Detailed directions for using planimeters accompany each instrument or may be found in books on steam-engine or indicator practice.

EXAMPLE.—Find the average power from the graph of Fig. 57 with a planimeter and compute the energy thereby represented. SOLUTION.—By using the planimeter it is found that the area (*ABCDEFGHIJKLMA*) within the graph, representing energy, is 27,547 sq. in. (Note that the cut shown is only about one-third the size of the original graph on which this example was based.) The length, *AL*, of the graph is found, by scaling, to be 9⅝ in. Now 9⅝ in. = 9.625 in. Hence, the average height or ordinate of the graph is: 27,547 ÷ 9.625 = 2.86 *in.*

It will be found by scaling along the ordinate *AN* that 2.86 in. is equivalent to 572 kw., that is, 1 in. = 200 kw. Hence, the average

power is 572 kw. as indicated by line *OP* which has been drawn in on the sheet. Furthermore, the energy represented by the shaded area within the graph is: 572 *kw.* × 24 *hr.* = 13,728 *kw.-hr.*

If it were known at the start that the energy represented by the shaded portion within the graph was 13,728 kw.-hr., the procedure to determine the average power might then have been thus: 13,728 *kw.-hr.* ÷ 24 *hr.* = 572 *kw.-hr.* which is the average power or load.

95. To Determine the Average Power From a Load Graph With an Amsler-Type Polar Planimeter (Figs. 58 and 59) the process is simpler than that just described because, with this instrument, it is unnecessary to scale the length—representing time—of the graph. By performing a simple subtraction and division the average height (which is proportional to the average power) of the graph may be obtained directly as outlined under Fig. 59.

96. To Determine the Maximum-demand value for use in computing a load factor, the most desirable and accurate method is to use the reading of a maximum-demand meter where such is available. Where load graphs are available, the maximum demand can be readily taken from them. The record of a graphic wattmeter is useful in this connection. A load graph may be plotted from the readings, taken at equidistant time intervals, of an indicating ammeter or wattmeter and the maximum demand may then be ascertained from the graph thus plotted. The examples herein recited illustrate the general methods. Where the demand factor applying to a connected load of a certain character is known, the maximum demand can then be obtained by multiplying the connected load in kilowatts by the demand factor; the result will be the maximum demand in kilowatts. The definition of connected load is given below. The following equations indicate how this process may be utilized in solving load-factor problems.

NOTE.—The maximum demand of an energy-receiving installation is sometimes, erroneously, assumed as equal to the connected load. While this assumption may approximate the facts in certain isolated instances, such is seldom the case. The value obtained by dividing *average load* by *connected load* does not give "load factor" but gives "connected-load factor" as explained in a following article.

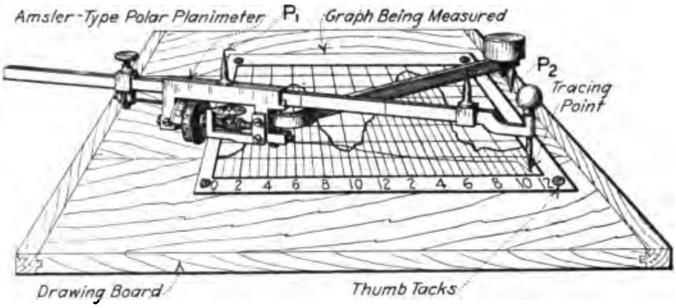


FIG. 58.—Amsler-type polar planimeter being used in measuring the area within a load graph.

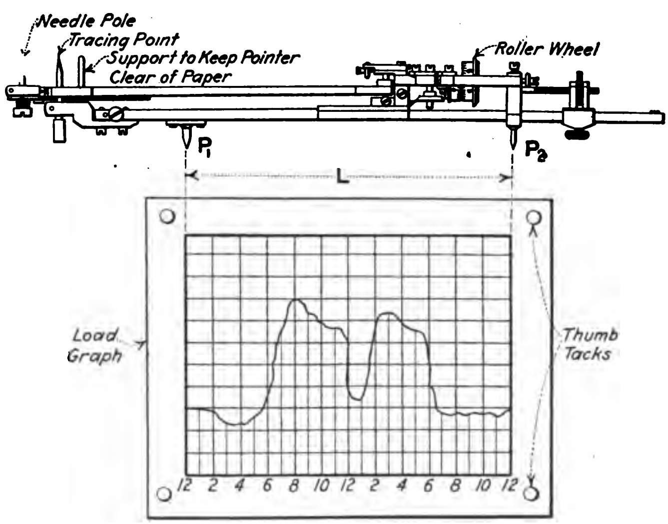


FIG. 59.—Method of setting planimeter so that it will read the mean or average height of graph.

The planimeter is held upside down and points P and P_2 are so adjusted that the distance between them is exactly equal to the length L of the load graph. Then the arm is clamped and the planimeter used in the usual way. However, instead of indicating the area, the mean height of the graph may be ascertained from the readings. Thus, with one make of instrument, the difference between the readings at the beginning and at the end of the operation divided by 0.4 will give the mean height of the graph in inches. Example: (Second reading, 4,322) − (first reading, 4,786) = 0.464. Now 0.464 ÷ 0.4 = 1.16 which is the mean height of the diagram in inches.

97. The Equation for Computing Load-factor Problems on the Basis of Demand Factor and Connected Load Where Only One Load is Under Consideration follow from the fact disclosed in equation (8) that: *Maximum demand = connected load × demand factor.* Substituting this expression, which is taken from Art. 53, in formula (14) it follows that:

$$(20)\qquad \textit{Load factor} = \frac{\textit{av. power}}{\textit{max. dem.}} = \frac{\textit{average power}}{(\textit{dem. factor}) \times (\textit{con. load})}.$$

$$(21)\qquad \textit{Average power} = (\textit{dem. fac.}) \times (\textit{con. load}) \times (\textit{load factor}).$$

$$(22)\qquad \textit{Dem. fac.} = \frac{\textit{average power}}{(\textit{load factor}) \times (\textit{con. load})}.$$

$$(23)\qquad \textit{Connected load} = \frac{\textit{average power}}{(\textit{dem. factor}) \times (\textit{load factor})}.$$

EXAMPLE.—The connected load of a certain theatre is 3.2 kw. Its average power consumption during the year (8,760 hr.) 1915 was 0.27 kw. If a demand factor of 49 per cent. be assumed as applying to this class of service—see accompanying Table 99—what will be the annual load factor for this installation? SOLUTION.—Substitute in equation (20): *Load factor* = (*av. power*) ÷ [(*dem. fac.*) × (*con. load*)] = 0.27 ÷ (0.49 × 3.2) = 0.27 ÷ 1.57 = 0.172 = 17.2 *per cent.*, which is the annual load factor which may reasonably be expected for this class of service.

98. If Several Different Loads or a Group of Loads Are Under Consideration and there is a diversity among their demands, a diversity factor may be introduced into the formulas. It can be shown that, equation (13), for several different loads: *Max. dem.* = (*connected load*) × (*demand factor*) ÷ (*diversity factor*). Hence, substituting this expression for maximum demand in equation (20):

$$(24)\qquad \textit{Load factor} = \frac{\textit{av. power}}{\textit{max. dem.}} = \frac{(\textit{av. power}) \times (\textit{diversity factor})}{(\textit{connected load}) \times (\textit{dem. factor})}.$$

$$(25)\qquad \textit{Connected load} = \frac{(\textit{av. power}) \times (\textit{diversity factor})}{(\textit{load factor}) \times (\textit{demand factor})}.$$

$$(26)\qquad \textit{Demand factor} = \frac{(\textit{av. power}) \times (\textit{diversity factor})}{(\textit{load factor}) \times (\textit{connected load})}.$$

$$(27) \qquad Av.\ power = \frac{(load\ fac.) \times (con.\ load) \times (dem.\ fac.)}{diversity\ factor}.$$

$$(28) \quad Diversity\ factor = \frac{(load\ fac.) \times (con.\ load) \times (dem.\ fac.)}{average\ power}.$$

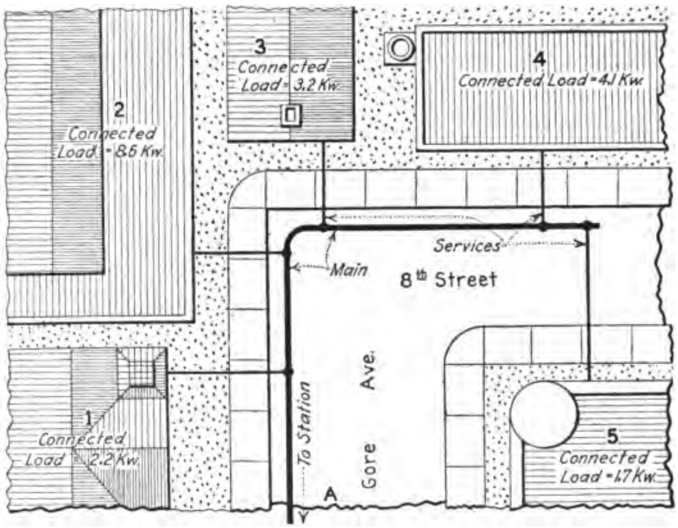


FIG. 60.—Example in computing load factor on the basis of connected load, demand factor and diversity factor.

EXAMPLE.—What will be the probable annual load factor (Fig. 60) of the load imposed at *A* by the five manufacturing plants shown, if the average load is 2.06 kw. It is assumed that the demand factor of their loads is 50 per cent. and the diversity between them is 1.44? SOLUTION.—The total connected load is: $2.2 + 8.6 + 3.2 + 4.1 + 1.7 = 19.8$ *kw.* Then, substituting in equation (24): *Load factor* = (*av. power*) $\times$ (*diversity factor*) $\div$ (*con. load*) $\times$ (*dem. factor*) $= (2.06 \times 1.44) \div (19.8 \times 0.5) = (2.96 \div 9.9) = 0.30 = 30$ *per cent.* Hence, the load factor of the load imposed at *A* is 30 per cent.

99. Load Factors, Demand Factors and Connected-load Factors of "Small" and "Medium" Lighting Customers in Chicago.—The values in columns *A* and *B* are averages from the information of actual tests.* They are based on data presented before a National Electric Light Association convention by R. W. Lloyd. The values in column *C* were obtained,

* Based on data presented before a National Electric Light Association convention by E. W. Lloyd.

in accordance with the method described in another paragraph, by multiplying together the corresponding values of columns *A* and *B*. It should be understood that while these values are "representative," in that they are based on averages of observed data, it does not necessarily follow that the same values will be obtained under all conditions for the loads of the different classes enumerated. However, they may, ordinarily, be safely used in estimating where precise values applying to the particular conditions under consideration are not available. All of the following values are expressed in per cent. The load factors and the connected-load factors are on an annual (8,760-hr.) basis.

Kind of business	*A* Load factor	*B* Demand factor	*C* Connected-load factor
Banks	16	67	11
Churches	12	56	7
Hotels	24	28	7
Houses	8	43	3
Offices (business)	9	64	8
Offices (professional)	7	64	4
Pool and billiards	17	65	11
Printers and engravers	15	59	9
Restaurants	23	52	12
Saloons	21	63	13
Shops (barber)	12	70	8
Shops (machine)	9	37	3
Shops (tailor)	8	59	5
Stables (livery)	22	52	11
Stores (book and stationery)	12	66	8
Stores (cigar)	17	65	11
Stores (house furniture)	8	52	4
Stores (dry goods)	8	77	6
Stores (drug)	19	79	15
Stores (furniture)	6	70	4
Stores (grocery)	10	73	7
Stores (hardware)	11	40	4
Stores (jewelry)	15	64	10
Stores (shoe)	10	67	8
Stores (clothing)	7	53	4

Kind of business	*A* Load factor	*B* Demand factor	*C* Connected-load factor
Small hotels and rooming houses.	26	67	17
Laundries	10	68	7
Theatres	17	49	8
Warehouses	12	41	5
Wholesale houses	19	47	9
Manufacturers	10	54	5
Hospitals	13	42	5
Flats	7	54	4

100. Load Factors, Demand Factors and Connected-load Factors of "Large" Combined Power-and-light Consumers in Chicago.—These values are averages of actual tests.* Their use should be subject to the restrictions specified in the heading of Table 99. All of the following values are expressed in per cent. The load factors and the connected-load factors are on an annual (8,760-hr.) basis.

Kind of business	*A* Load factor	*B* Demand factor	*C* Connected-load factor
Butter and creamery	20	60	12
Breweries	45	60	27
Brass and iron beds	20	60	12
Biscuit manufacturers	35	55	19
Boots and shoes	25	65	16
Brass manufacturing	28	50	14
Boiler shops	18	45	8
Can manufacturers	30	70	21
Candy manufacturers	18	45	8
Clothing manufacturers	15	55	8
Clubs (large)	40	85	34
Department stores (large)	30	55	17
Electrical manufacturing	25	55	14
Express companies	40	60	24
Electroplating	25	75	19
Engraving and printing	19	60	11
Fertilizer manufacturing	75	40	30

* E. W. Lloyd.

Kind of business	*A* Load factor	*B* Demand factor	*C* Connected-load factor
Furniture manufacturing	28	65	18
Foundries	15	75	11
Forge shops	30	49	15
Grain elevators	10	75	8
Glove manufacturing	25	55	14
Grocers (wholesale)	20	55	11
Hotels (small)	35	50	18
Hotels (large)	50	40	20
Ice-cream manufacturing	45	75	34
Jewelry manufacturing	18	50	9
Laundries	25	70	18
Machine shops	26	55	14
Newspapers	20	75	15
Packing houses	30	75	23
Paint, lead and ink manufacturers	23	45	10
Paper-box manufacturers	25	50	13
Plumbing and pipe fitting	26	55	14
Post offices	50	30	15
Power buildings	27	40	11
Refrigeration	50	90	45
Railroad depots	50	50	25
Pneumatic tube	50	90	45
Soap manufacturers	25	60	15
Seed cleaners	25	55	14
Screw manufacturers	30	75	23
Spice mills	20	55	11
Saw manufacturers	30	55	17
Structural steel	22	40	9
Sheet-metal manufacturers	18	70	13
Stone cutters	17	55	9
Twine mills	30	60	18
Theatres	16	60	10
Large restaurants	50	60	30
Small restaurants	30	70	21
Woolen mills	27	80	22
Wood-working	28	65	18
Textile mills	20	65	13

101. Annual or Yearly Load Factor *is equal to the average power load over the entire year divided by the maximum power demand during that year.* A year is taken as having: 365 *days* $\times$ 24 *hr.* = 8,760 *hr.*

EXAMPLES OF TYPICAL YEARLY LOAD FACTORS for central-station loads are given by J. R. Cravath thus: A purely lighting load in a small town will yield at the supplying station a yearly or 8,760-hr. load factor of less than 20 per cent.; in a large city it will be less than 25 per cent. By the addition of electric-motor and heating-appliance loads, these load factors have been improved (see Fig. 61) from year to year during the

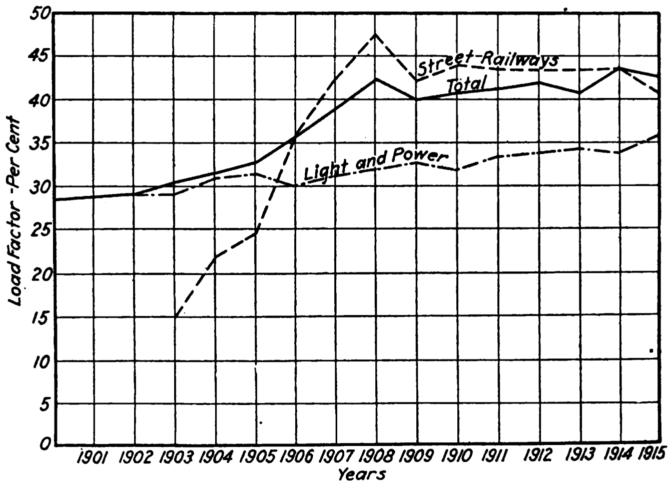


FIG. 61.—Graph showing annual load factors of the Commonwealth Edison Co., Chicago. This indicates how the load factor of a system may be improved through systematic persistent effort.

history of the central-station industry. A load factor of between 30 and 35 per cent. is now common in the smaller plants having a moderate power load. In some manufacturing cities, load factors greater than 50 per cent. have sometimes been attained, but such instances are rare. A combination of lighting, power and railway loads in a large city provides a load factor between 40 and 45 per cent.

102. Operating Load Factor *is the ratio of the average power load imposed on a plant or by equipment, during the time which the plant or equipment operates, to the maximum power demand imposed during that time.* Frequently, central-station plants

in small cities operate only during the night and industrial-plant generating stations may operate only during the day. Operating-load factors have their application for conditions such as these.

EXAMPLE.—A certain small central station in a town of 750 inhabitants in Iowa operates 3,540 hr. per year. The energy generated during the 3,540 hr. of operation is 15,576 kw.-hr. The maximum power demand or maximum load is 16.9 kw. (1) What is the annual load factor? (2) What is the operating load factor? SOLUTION.—(1) The average power or load during operation is: 15,576 *kw.-hr.* ÷ 3,540 *hr.* = 4.4 *kw.* Hence, *operating load factor* = (*average power load during operation*) ÷ (*maximum demand*) = 4.4 ÷ 16.9 = 0.26 = 26 *per cent.* (2) The average load over the entire year is 15,576 *kw.-hr.* ÷ 8,760 *hr.* = 1.775 *kw.* Hence, the *annual load factor* = (*average power load over entire year*) ÷ (*maximum demand*) = 1.775 ÷ 16.9 = 0.105 = 10.5 *per cent.*

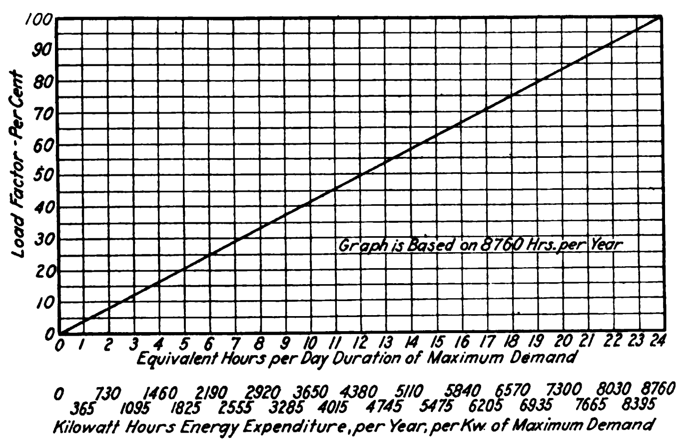


FIG. 62.—Graph showing relation of load factor to equivalent hours use of maximum demand.

103. To Compute the Energy Delivered or Consumed by a Given Installation of Known Load Factor when the maximum demand is known, reckon the average power by using formula (15) and then figure the energy consumption by applying formula (19). Where the maximum demand is not known but where the connected load and demand and diversity factors are known equation (21) or (27) can be used for calculating the average power. Frequently, the graph of

Fig. 62 can be used to advantage as illustrated in the following examples:

EXAMPLE.—An annual load factor of 25 per cent. (Fig. 62) implies a 6-hr. use per day of the maximum demand and an annual energy expenditure of 2,190 kw.-hr., per kw. of maximum demand. Thus if a certain installation has a load factor of 25 per cent. and its maximum demand is 42 kw. the annual energy expenditure involved is: 42 × 2,190 = 91,980 *kw.-hr.*

104. A Specific Example Showing How Fixed Charges per Kilowatt-hour Increase with Decreasing Load Factor,* is stated graphically in Fig. 50. This is based on an assumed plant having a maximum capacity of 100 kw., and an assumed cost of $10,000. A fixed charge of 12 per cent. is assumed thus: interest 5 per cent., depreciation 5 per cent., insurance and taxes 2 per cent. The fixed charge per kilowatt-hour generated may be determined in this way:

EXAMPLE.—The yearly fixed charge (Fig. 50) will be: 0.12 × $10,000 = $1,200. If the plant operated at a load factor of 100 per cent.—8,760 hr. per year—it would develop: 8,760 *hr.* × 100 *kw.* = 876,000 *kw.-hr.* per year. Then the fixed charge per kilowatt-hour would be: $1,200 ÷ 876,000 *kw.-hr.* = $0.00137 = 0.137 *cts.*, as plotted in Fig. 50 at *A*. Now if the load factor is 25 per cent., only one-half the energy would be generated, that is, there would be generated 8,760 *hr.* × 25 *kw.* = 219,000 *kw-hr.* per year. Then the fixed charge per kilowatt hour would be: $1,200 ÷ 219,000 = $0.00548 = 0.548 *cts.*, as plotted at *B*. That is, with a load factor of 25 per cent. the fixed charge has been increased fourfold. The other points on the graph may be determined by a similar process.

105. Plant Factor† is "the ratio of the average load to the rated capacity of the power plant, *i.e.*, the aggregate ratings of the generators." That is:

$$(29) \qquad \textit{Plant factor} = \frac{\textit{average load}}{\textit{rated capacity of plant}}$$

$$(30) \quad \textit{Average load} = (\textit{plant factor}) \times (\textit{rated capacity of plant})$$

$$(31) \quad \textit{Rated capacity of plant} = \frac{\textit{average load}}{\textit{plant factor}}.$$

* Albert F. Strouse.

† A. I. E. E. STANDARDIZATION RULES, Sec. 56.

EXAMPLE.—The generating equipment in the central station shown in Fig. 63 comprises two 600-kw. (continuous-rating), turbo-generator units, *A* and *B*. If it is assumed that the average power load imposed on the station is 255 kw., what then is its plant factor? SOLUTION.—From formula (29): *Plant factor* = (*average load*) ÷ (*rated capacity of plant of generators*) = 255 *kw.* ÷ (600 *kw.* + 600 *kw*) = 255 ÷ 1,200 = 0.212. That is, the plant factor is, on a continuous rating basis, 21.2 per cent.

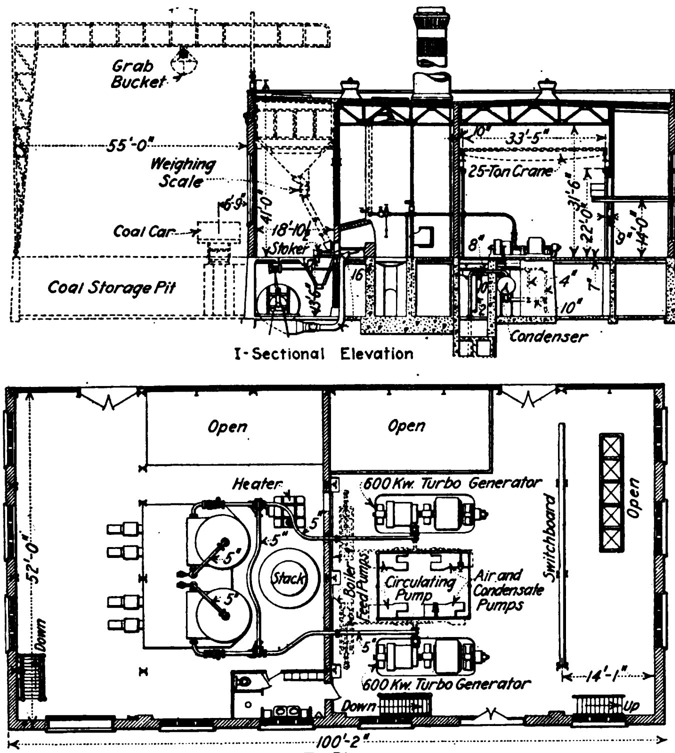


FIG. 63.—Kalamazoo, Mich., municipal lighting plant

106. There May Be an Annual and an Operating Plant Factor just as there may be an annual and an operating load factor, as discussed in Art. 102. In fact, plant factor may be determined over any suitable period of time just as can load factor. Note that plant factor applies only to energy-

generating or delivering apparatus and that it does not apply to energy-consuming apparatus. While the explanatory definition as given in the A. I. E. E. STANDARDIZATION RULES refers specifically to the "aggregate ratings of the generators," plant factor may properly be computed on the basis of the output of any energy-delivering plant—not necessarily a generating plant. Thus, a plant factor may be computed relating to the output of a transformer, motor generator, synchronous converter or any similar sort of a sub-station.

107. A Plant Factor Does Not Have a Definite Meaning Unless the Method Used in Rating the Capacity of the Station is Specified.—The station may be rated on a "normal-power-capacity" basis or on a "continuous" or "maximum-power-capacity" basis and the continuous capacity may be from 25 to 40 per cent. or more greater than its normal capacity. However, since the "continuous" method of rating electrical apparatus is, probably, in most cases the more logical, it should always be used where feasible. The continuous rating is defined below. Where no method of rating is specified, it is logical to assume that the *continuous* method is implied.

108. The Continuous Rating of a piece of electrical apparatus is that rating—usually expressed in horse-power or kilowatts but sometimes in amperes—at which the machine or device may operate continuously without its limitations being exceeded. That is, without its becoming so overloaded that it will be overheated and damaged or becomes unsafe, inefficient or operate with a poor performance. A continuous rating is often referred to as a *maximum rating.*

NOTE.*—"A machine rated for continuous service shall be able to operate continuously at its rated output without exceeding its limitations dictated by: (1) *Operating temperature,* (2) *mechanical strength,* (3) *commutation,* (4) *dielectric strength,* (5) *insulation resistance,* (6) *efficiency,* (7) *power factor,* (8) *wave shape,* and (9) *regulation.*

EXAMPLE.—Most types of electrical machinery may be given either "normal" or "maximum" ratings. The normal rating indicates the load which the machine will carry continuously and with a certain overload for a specified time. The maximum or continuous rating indicates the load which the machine will carry continuously but without any over-

* A. I. E. E. STANDARDIZATION RULES, Sec. 281.

load. Thus a generator of a certain size and of a certain manufacture is given a *normal* rating of 100 kva. This means that the machine is capable of carrying continuously a load of 100 kva., and that it will also carry an overload of 50 per cent.—150 kva.—for 1 hr. after it has been continuously carrying its 100 kva. normal load. Furthermore, this same machine will carry 135 kva. continuously (35 per cent. over its normal rating) and hence can be called a 135-kva. maximum—or continuous—rating machine.

The generator discussed had a normal rating of 100 kva. and a continuous or maximum rating of 135 kva. The present tendency is to give all electrical machinery only one rating—the continuous. This will tend to minimize the confusion relating to ratings which now exists. Practically all generators and transformers are now rated only on the maximum (the continuous-carrying-capacity) basis.

109. The Importance of Maintaining the Plant Factor as High as Possible will be apparent from a consideration of the discussion given in Art. 87 relating to load factor. In general, the lower the plant factor of a station the greater will be its cost of producing energy.

110. Capacity Factor, a value sometimes used, has about the same significance as plant factor. Capacity factor is not mentioned in the A. I. E. E. STANDARDIZATION RULES but is defined by G. I. Rhodes* as: "*the ratio of the average load to the rated capacity of the equipment supplying that load.*" It might be properly called output-capacity factor. As with plant factor, this value will not have a definite meaning unless the method used in rating the output capacity of the equipment in question is specified. The "continuous" method of rating (defined below) should always be used where feasible.

NOTE.—"Capacity factor" is, probably, a better and more general term than "plant factor" because, strictly speaking, the word "plant" limits the use of the value (plant factor) to the total output of a plant of some sort. But "capacity factor" may be properly used as relating to the output of an energy delivering plant or to the output of any individual unit or group of equipment in the plant or station. Thus, there may be a capacity factor for a station and a capacity factor for any generator or motor generator in a station. It is not unlikely that, because of its more general application, the term "capacity factor" may supersede "plant factor."

* STANDARD HANDBOOK, 1915; p. 875.

111. The Distinction Between Plant Factor, Load Factor and Capacity Factor should be clearly understood because the terms are sometimes, though incorrectly, used interchangeably. The term "load factor" is frequently used where "plant factor" is really meant. Some writers of standing thus use "load factor" incorrectly, but, since the term is accurately defined in the A. I. E. E. STANDARDIZATION RULES, it appears best to adhere rigidly to the definition there given. "Load factor" is the ratio of *average power to maximum demand* while "plant factor" is the ratio of *average power to rated station capacity*. Furthermore, "load factor" may relate either to the energy delivering or energy receiving equipment while "plant factor" relates specifically to delivering equipment. The distinction between "plant factor" and "capacity factor" is that "plant factor" relates specifically to the total output of an energy-delivering station while "capacity factor" may relate to the output of any energy-delivering station, machine, system or equipment. Note that "plant factor" is really a special restricted case of "capacity factor."

112. Connected-load Factor is *the ratio of the average power input to the connected load.* It is expressed as a percentage and relates only to receiving equipment. As with load factor, to render this value specific the period over which the power is averaged should be specified. Usually the average is taken over a year and if no period is mentioned a year is ordinarily implied. From the definition just given it follows that:

$$\text{(32)} \qquad \textit{Connected load factor} = \frac{\textit{average power input}}{\textit{connected load}}$$

$$\text{(33)} \quad \textit{Average power input} = (\textit{con. load factor}) \times (\textit{con. load})$$

$$\text{(34)} \qquad \textit{Connected load} = \frac{\textit{average power input}}{\textit{con. load factor}}.$$

"Connected load" is defined in a following paragraph. The average power input and the connected load must be expressed in the same units. If the power input is expressed in kilowatts, the connected load should then also be expressed in kilowatts. If the power input is expressed in horse-power, the connected load should be expressed in horse-power. The

connected-load value used should be based on the output capacity of the equipment involved, and not on the input capacity.

113. Connected-load Factors Are Most Useful in Finding the Probable Average Power Input or the Probable Annual Energy Consumption of an installation when the connected load and the connected-load factor applying to it are known. A distinguishing feature of connected-load factor is that *it relates only to energy consuming apparatus.* A comparison of equation (32) with those of (14) and (29) will disclose the distinction between this and the other factors herein considered.

114. To Insure That a Connected-load Factor Has a Definite Meaning it is necessary to specify the basis on which the connected load is computed. "Connected load" should, strictly speaking (see definition given in Art. 116) always be stated on a continuous-rating basis. However, it is not always feasible to follow this method. A lighting "connected load" is equal to the sum of the wattages of all of the lamps in the installation. A motor "connected load" is equal to the sum of the rated (nameplate) outputs of all of the motors. Motors are usually rated in horse-power output; hence, it is usually most convenient to reduce these horse-power values to equivalent kilowatt values before adding them together. Motors are now ordinarily rated on a "normal" output basis but a "continuous" rating is now sometimes given to motors. It is not improbable that, in the future, all motors may be rated on a "continuous" basis. Hence, the method employed in rating the motors should, where motors are involved, be specified when a connected load factor is stated. At this time, when a connected load factor is given for a motor load and the method whereby the motors were rated is not specified it may be assumed that "normal" ratings are inferred. Examples which follow illustrate the method.

EXAMPLE.—What is the connected-load factor of the installation shown in Fig. 54 on a 1-day (10-hr.) basis? The watt-hour meter records 234 kw.-hr. as having been used during a certain 10-hr. day. Full load output (nameplate, normal basis) ratings in kilowatts are indicated in the

illustration near each piece of apparatus in the illustration. SOLUTION.—The average load for the 10-hr. day is: 234 ÷ 10 = 23.4 *kw.* Now substitute in equation (32): *Con. load factor* = (*average load*) ÷ (*connected load*) = 23.4 ÷ (2.5 + 5.5 + 30 + 7.5 + 13) = 23.4 + 58.5 = 0.4 = 40 *per cent.* Hence, the connected-load factor of this installation is 40 per cent.

EXAMPLE.—The combined motor and lighting load diagrammed in Fig. 64 is installed in a foundry. What average annual load may this installation be expected to impose on the central station and what will

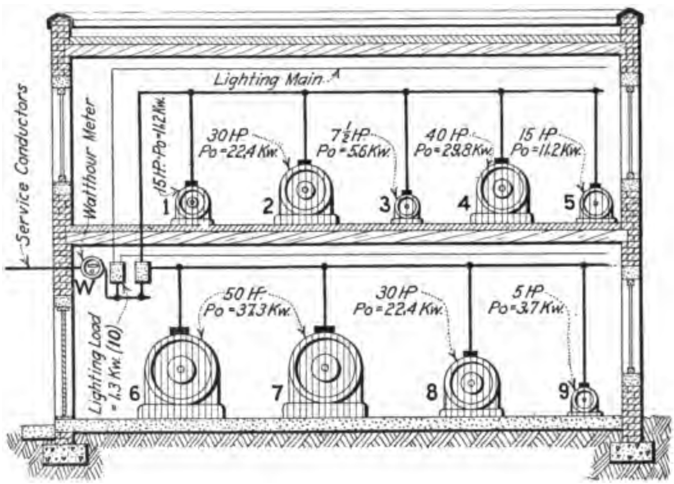


FIG. 64.—Illustrating an example of the application of connected-load factor.

be the probable annual (8,760-hr.) energy consumption? SOLUTION.—The annual approximate connected-load factor is shown in Table 100, column C, to be 11 per cent. The equivalent rated connected load (normal ratings of motors) in kilowatts, is, as shown by the power output symbols P_0: 11.2 + 22.4 + 5.6 + 29.8 + 11.2 + 37.3 + 22.4 + 3.7 + 1.3 = 144.9 *kw.* Now substitute in equation (33): *Av. power input* = (*con. load factor*) × (*con. load*) = 0.11 × 144.9 = 15.9 *kw.* Hence, the average power load imposed by this plant on the central-station system would, probably, be about 16 kw. To ascertain the kilowatt-hour energy consumed annually, substitute in equation (19): *Kw.-hr. expended during period* = (*av. power*) × *no. hr. in period*) = 15.9 × 8,760 = 139,284 *kw-hr.*

115. Connected-load Factor Equals the Product of Demand Factor and Load Factor as will be shown. By definition, see equation (32):

$$(35) \qquad \textit{Connected-load factor} = \frac{\textit{average power input}}{\textit{connected load}}.$$

But, as shown in equation (15):

(36) *Average power input* = (*load factor*) × *maximum demand*). Furthermore, it can, on the basis of definition (Art. 116 and equation (9)), be shown that:

$$(37) \qquad \textit{Connected load} = \frac{\textit{maximum demand}}{\textit{demand factor}}.$$

Substituting the expressions for *average power input* of (36) and for *connected load* of (37) in equation (35) the result is:

$$(38) \quad \textit{Con.-ld fac.} = \frac{(\textit{load factor}) \times (\textit{max. dem.}) \times (\textit{dem. fac.})}{\textit{maximum demand}}.$$

The expression *maximum demand* appears in both numerator and denominator of the above equation, hence "cancels out" and the resulting working formula is:

(39) *Connected-load factor* = (*load factor*) × (*demand factor*).

116. Connected Load is defined* as "the combined continuous rating of all the receiving apparatus on consumers' premises, connected to the system or part of the system under consideration." The *output* ratings should, where feasible, be used instead of the *input* ratings.

EXAMPLE.—The connected load on the service shown in Fig. 54 is: 2.5 *kw.* + 30 *kw.* + 13 *kw.* + 7.5 *kw.* + 5.5 *kw.* = 58.5 *kw.*

117. A Graph for Quickly Computing the Kilowatt-hour Energy Consumption of an Installation When the Connected-load Factor and the Connected Load Are Known is given in Fig. 65. The application is explained in the following examples. This graph may also, when the connected-load factor is known, be applied conveniently for determining, by inspection, the equivalent hours used per day of the total connected load.

* A. I. E. E. STANDARDIZATION RULE.

EXAMPLE.—In a certain plant the total rated capacity of all of the motors is 60 h.p. The connected-load factor is known to be 25 per cent. What will be annual energy consumption? SOLUTION.—The graph of Fig. 65 indicates that, with a connected-load factor of 25 per cent., the annual energy consumption will be 1,634 kw.-hr. per h.p. installed. Hence, the annual energy consumption will be: 60 h.p. × 1,634 = 98.040 *kw.-hr.*

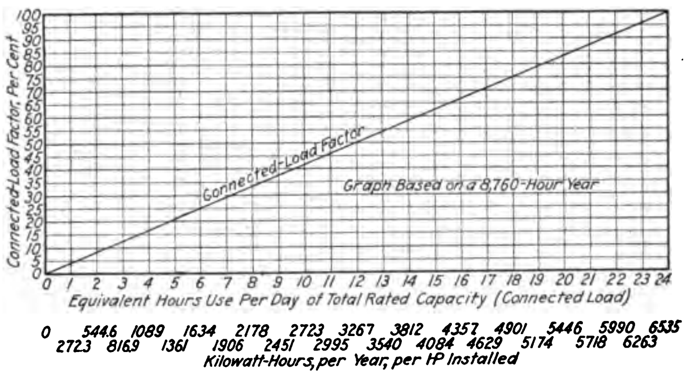


FIG. 65.—Graph showing relation of connected-load factor to equivalent hours use of connected load.

It will also be noted from Fig. 65 that a connected-load factor of 25 per cent. is equivalent to a 6-hr. use per day of the total capacity or connected load installed.

EXAMPLE.—If the connected-load factor of an installation is 40 per cent., it means that the energy consumed by this installation is the same as that which would be consumed by all of the connected load if it were operated at rated (nameplate) output for 9½ hr. per day (see Fig. 65) every one of the 365 days of a year.

SECTION 6

LOAD GRAPHS AND THEIR SIGNIFICANCE

118. A Load Graph, or as it is sometimes called, a load curve, is merely a graphic record of the power loads which have been imposed on a station or on some electrical unit at all of the different instants during a certain period of time. The illustrations (Figs. 66 to 87, which are based largely on data pro-

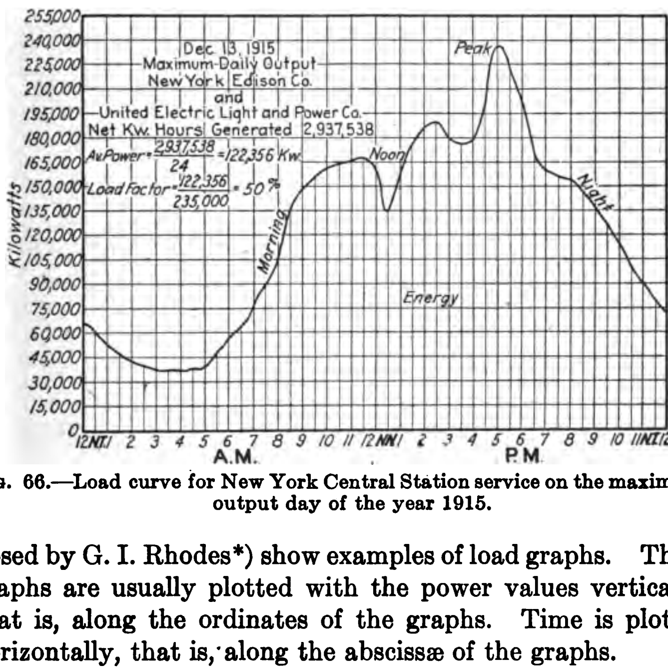


FIG. 66.—Load curve for New York Central Station service on the maximum-output day of the year 1915.

posed by G. I. Rhodes*) show examples of load graphs. These graphs are usually plotted with the power values vertically, that is, along the ordinates of the graphs. Time is plotted horizontally, that is, along the abscissæ of the graphs.

NOTE.—The area included within the load graph—indicated by the shaded portions in the illustrations—represent energy. That is, the product of: *Power* × *time*. Thus, in Fig. 66 the shaded portion of the graph is proportional to:

Average power × *hours* = 122,356 *kw.* × 24 *hr.* = 2,937,538 *kw.-hr.*

* STANDARD HANDBOOK.

119. There are Two General Methods Whereby the Data for Plotting Load Graphs May be Obtained.—*Method* 1.—Where graphic instruments are installed the load imposed at any instant can be readily ascertained from the record made by the instrument. In fact, the record strip of a graphic wattmeter is its load graph. *Method* 2.—Where graphic instruments are not installed, the power values for plotting the graph may be read at equidistant intervals from indicating instruments connected into the circuit under consideration. The frequency with which the readings should be taken will be determined to a large extent by the character of the load under consideration. If the load is subject to wide and con-

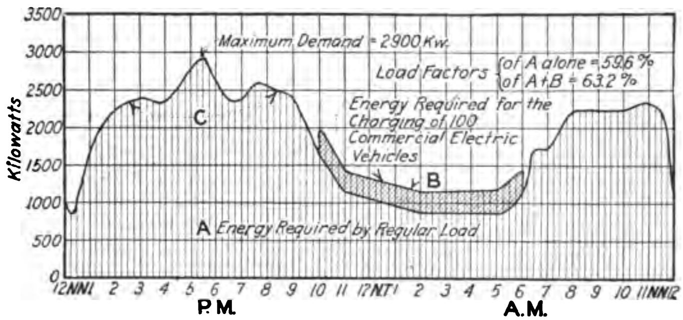


FIG. 67.—Showing effect on a typical central station load graph of adding the charging load of a hundred commercial electric vehicles. (Station is steam driven and in a city of 100,000 inhabitants. Graph is for Feb. 1, 1916.)

tinual fluxation, it may be desirable to take readings every minute or even every half minute, but if the load is reasonably steady—that is, changes in value slowly—it will usually be sufficient to take a reading at the end of every 15-min. time interval. Where an indicating wattmeter is available, the power values thus obtained from it may be plotted against time into the graph. If no wattmeter is available but an ammeter or a voltmeter is, then both instruments should be read simultaneously at the end of each time interval. Then the product of the current and voltage thus obtained will, on direct-current circuits, be the watts-power expenditure at the specified instant.

NOTE.—On alternating-current circuits unless the power factor happens to be 100 per cent., which is not likely to be the case, the product of the volts and amperes will not represent watts; hence, with alternating-current circuits, it is inconvenient to obtain the power-expenditure values unless an alternating-current wattmeter is used.

EXAMPLE.—The graph *C* of Fig. 67 was plotted from the following values:

Time	Kilowatts power	Time	Kilowatts power
12:00 (Noon)	1,000	3:15	2,380
12:15	850	3:30	2,360
12:30	1,050	3:45	2,350
12:45	1,250	4:00	2,340
1:00	1,600	4:15	2,450
1:15	1,800	4:30	2,520
1:30	1,950	4:45	2,600
1:45	2,050	5:00	2,700
2:00	2,250	5:15	2,800
2:15	2,300	5:30	2,900
2:30	2,325	5:45	2,820
2:45	2,350	6:00	2,630
3:00	2,400	etc.	etc.

120. The Importance of a Thorough Appreciation of the Significance of Load Graphs should be understood. A load graph indicates at a glance the general character of the load which is being imposed and brings out the facts much more forcefully than will a couple of columns of figures. The higher the load factor (ratio of average load to maximum demand) the lower, in general, the cost of energy production will be. Obviously, the more nearly the graph of a load approximates a horizontal line the nearer will the conditions be to the ideal. That is, to economize energy production the "valleys" of a load graph should be filled in and the "peaks" should be lopped off. An inspection of a load graph will indicate just at what hours of the day the "valleys" and the "peaks" occurred and, with this information available, suitable measures may be taken to "even up the graph."

NOTE.—For these reasons every generating station should keep load graphs as an important feature of the station records. The graphs can,

where a graphic wattmeter is not installed, be plotted daily from the station log.

121. The Unit for the Ordinate Values of a Load Graph is ordinarily a kilowatt. In certain instances it may, where constant-potential circuits are involved, be desirable to use the ampere as the ordinate unit, because then the ampere values can, on direct-current circuits, be translated into watts or kilowatts by multiplying by the constant-potential voltage.

122. The Period Which Should Be Comprehended by a Load Graph is a thing which local conditions must decide. Where plants operate 24 hr. a day it is usual to plot the graphs relating thereto so that their horizontal lengths represent a

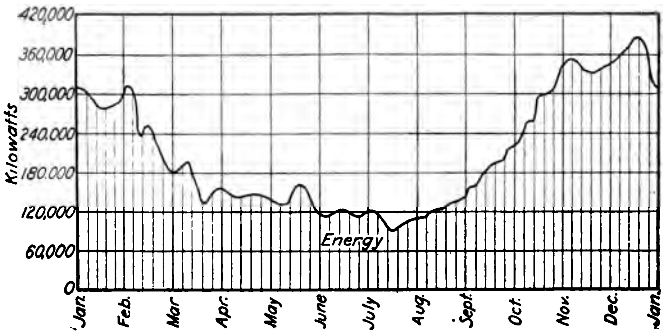


FIG. 68.—Annual or yearly load graph.

24-hr. period. When a plant operates only 8 or 12 hr. daily then it is sufficient if the length of the graphs represents only the 8- or 12-hr. period. Most load graphs are plotted on a 24-hr. basis as an examination of the accompanying illustrations will verify. Frequently it is desirable to plot graphs on a yearly basis as illustrated in Fig. 68 that one may study the distribution of the energy expenditure over the entire year.

123. Loads of Different Types Have Their Typical Load Graphs.—That is, the graph for any electric-lighting load will follow the general contour of that shown in Fig. 69. Industrial or factory loads will all have graphs of the general outline suggested in Fig. 70. This same condition holds, in a broad way, for all of the different loads of different classification

which a station may be called upon to serve. It is for this reason that the discussion of the load graphs of the different types which follows is given. These are, for the most part,

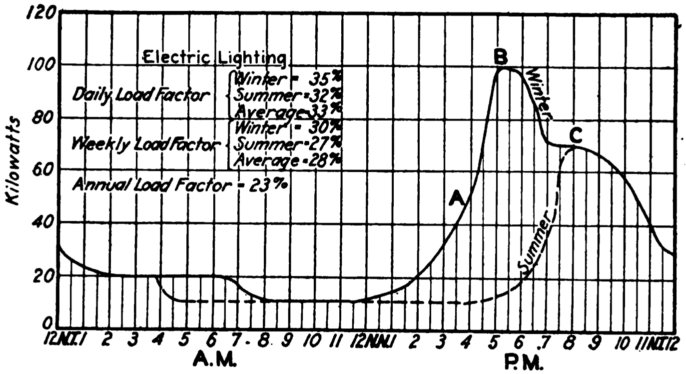


FIG. 69.—Typical 24-hour load graph for an electric lighting load.

based on power-plant economics data developed by George I. Rhodes.

124. The Load Graph of a Typical Electric-lighting Load in a town or city is shown in Fig. 69. Where there is little or no

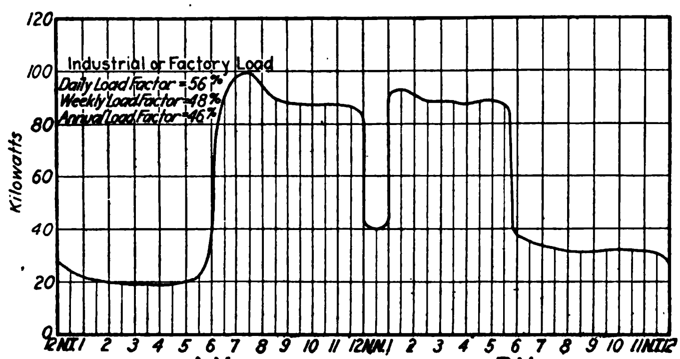


FIG. 70.—Typical 24-hour load graph for an industrial or factory load.

demand for energy for motors or railways, the power consumption will vary over the 24 hr. approximately as diagrammed in the illustration. The full-line graph indicates a

typical winter-day power demand while that which is dotted shows the demand on a typical summer day. The maximum demand occurs in the winter time between 4 and 6 o'clock in the evening because at this time most of the stores and offices and many of the residences are using a maximum of light. A maximum "peak" for the year usually occurs in December (Fig. 66). In the summer the lighting "peak" is imposed in the evening—about 8:00 P.M.—and it is of considerable lower value than the winter peak.

NOTE.—The minimum demand for lighting energy occurs between 9 o'clock in the morning and 2 o'clock in the afternoon in winter and between 4 o'clock in the morning and 5 o'clock in the afternoon in summer. A noticeable characteristic of lighting loads is the abruptness with which the energy consumption increases (from *A* to *B*, Fig. 69) in the evening and also the suddenness with which it decreases (from *B* to *C*, Fig. 69), after the shops and offices close in the evening. The load factors for typical electric-lighting loads of the general characteristics indicated in the graph of Fig. 69 are noted in the illustration. As there suggested, the annual load factor is about 23 per cent.

125. A Typical Graph for an Industrial Load is represented in Fig. 70. The load is a minimum during the hours when the industrial plant is not in operation. But the demand increases very abruptly at about 6 o'clock in the morning and attains the maximum for the day about 7:00 or 8:00 A.M. At the noon hour the graph drops almost vertically downward and rises again at 1 o'clock when the machines and lining equipment is again cut into service. It should be noted that the afternoon peak occurs shortly after 1 o'clock, but it is seldom as great as the morning peak. The power demands imposed by an industrial plant are about the same in winter as in summer. The annual load factor will be about 46 per cent.

126. A Typical Load Graph for a City Street Railway is delineated in Fig. 71. There are two pronounced peaks occurring at about 8:00 A.M. and 6:00 P.M. These are due, respectively, to the demands imposed by the transportation of employees to and from work. The minimum demand occurs about 3 o'clock in the morning. A graph for a typical summer day has the same general contour as that for a winter day. But the summer-day demands are, at every hour of the 24,

less than those in winter. The principal reason for this condition is that the electric heaters on the cars require considerable energy in the winter. In some cities it may occur that the summer traffic is heavier than the winter, but it is seldom

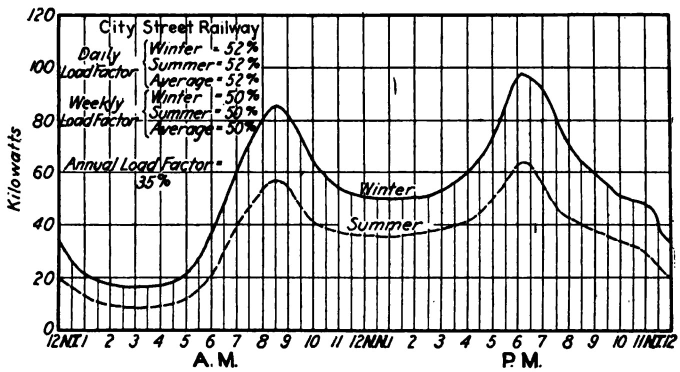


FIG. 71.—Typical 24-hour load graph for a city street railway load.

that the summer peak is higher than the winter peak. The annual load factor of a load of the general characteristics indicated in Fig. 71 is about 35 per cent.

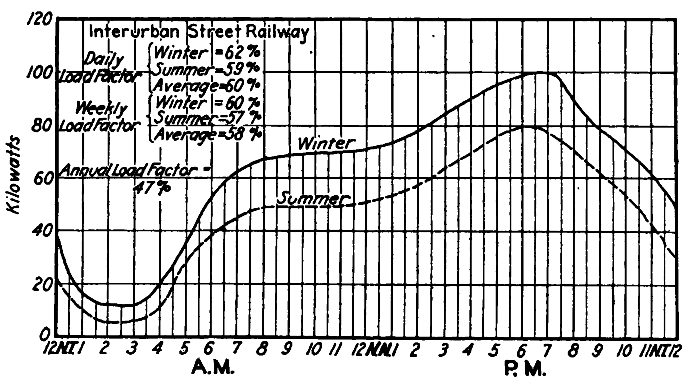


FIG. 72.—Typical 24-hour load graph for an interurban railway load.

127. Interurban Street Railways usually show a graph about like that outlined in Fig. 72. The peak occurs at about 7 o'clock in the evening and is caused by the heavy traffic

due to people riding home from the towns where they have been employed or visiting. The annual load factor for a load of this character is about 47 per cent.

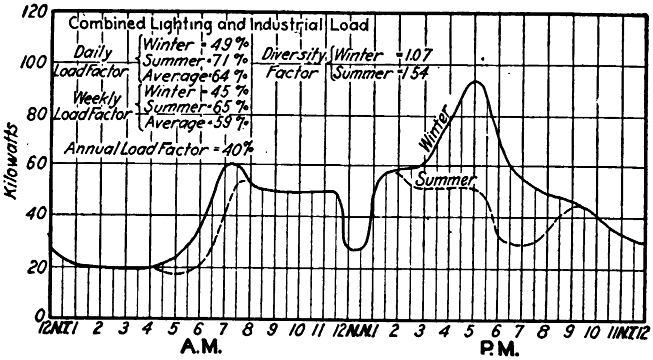


FIG. 73.—Typical 24-hour load graph for a combined electric lighting and industrial load.

128. By Combining a Lighting and an Industrial Load on the same energy supply source the resultant load imposed on the generating equipment will be of the character indicated

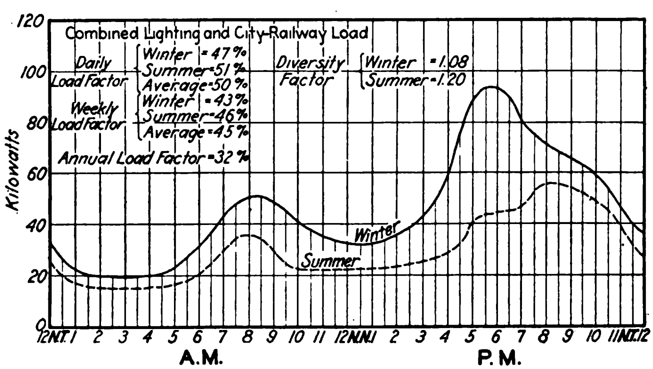


FIG. 74.—Typical 24-hour load graph for a combined lighting and city railway load.

in Fig. 73. Note that due to the diversity of the demands between the loads of these two different types there is a tendency toward "smoothing out the hollows" in the load curves and that the annual load factor for such a combined

load is about 40 per cent. as against 23 per cent. for the uncombined lighting load of Fig. 69. Therefore, it follows that a material economy in energy production results where loads of dissimilar characteristics can thus be consolidated.

129. A Combined Lighting and Street Railway Load will produce a graph of the general contour suggested in Fig. 74. The annual load factor resulting is only 32 per cent. as against 40 per cent. for a combined lighting and industrial load (Fig. 73). This is largely due to the fact that an industrial load is about the same in the summer as in winter, whereas, both lighting and railway loads are considerably greater in the winter than in the summer.

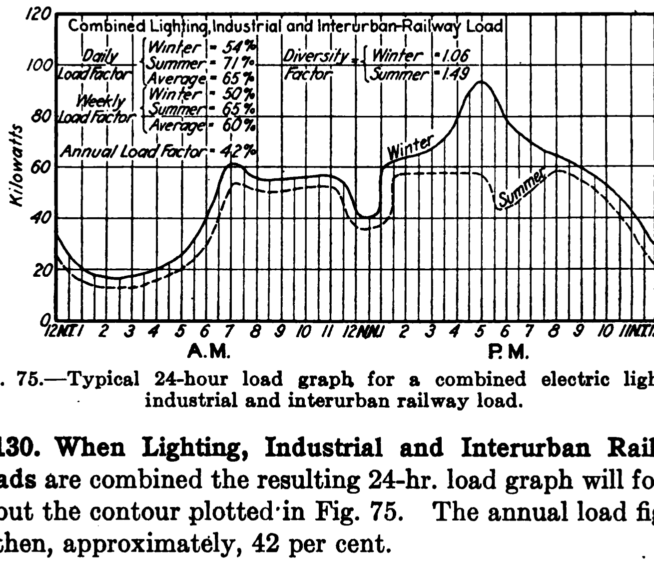


FIG. 75.—Typical 24-hour load graph for a combined electric lighting, industrial and interurban railway load.

130. When Lighting, Industrial and Interurban Railway Loads are combined the resulting 24-hr. load graph will follow about the contour plotted in Fig. 75. The annual load figure is then, approximately, 42 per cent.

131. A Combination of Lighting, Industrial, Interurban and Street Railway Loads will impose on the supplying equipment demands which will vary through the 24 hr. of the day somewhat as outlined in Fig. 76. The annual load factor will probably be in the neighborhood of 45 per cent.

132. Load Graphs for Large Cities are shown in Figs. 66 and 77. These have been plotted respectively for New York and Chicago from actual operating data. Both indicate the

results that may be expected by combining loads of different characteristics on one supply system. The graph of Fig. 66 comprehends loads handled by two companies which operate

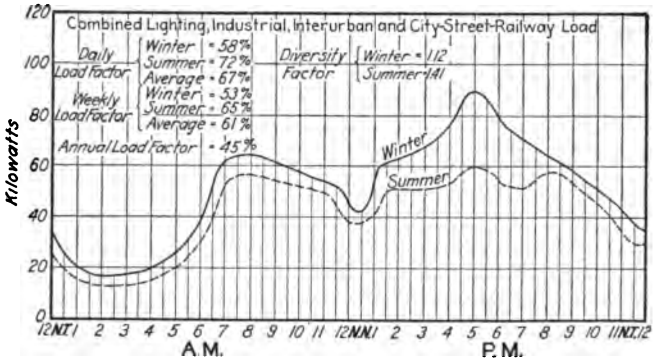


FIG. 76.—Typical 24-hour load graph for a combined lighting, industrial, interurban and city railway load.

in New York—The New York Edison Company and the United Electric Light and Power Company. The load factor is approximately 50 per cent. Fig. 77 shows total load for a

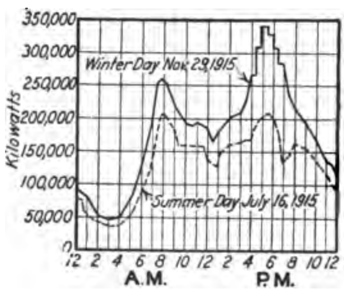


FIG. 77.—Load graphs for Chicago, Ill., on typical summer and winter day in 1915. (Commonwealth Edison Co.)

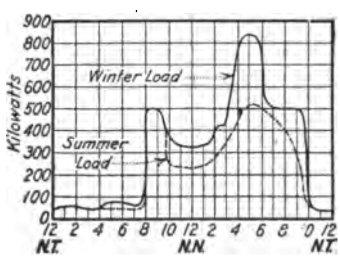


FIG. 78.—Typical graph of the loads on an office-building isolated plant.

typical summer and winter day which the Commonwealth Edison Company of Chicago serves.

133. A Load Imposed on an Office Building Isolated Plant will have the general characteristics graphed in Fig. 78. The

peak at 8:00 A.M. is due, for the most part, to the energy taken by the electric elevators. The evening peak between 4 and 6 o'clock is due largely to the power required for light but the elevator power also has its effect at this time.

134. A Hotel Isolated Plant will usually have imposed on it a load which will vary with the time somewhat as outlined in Fig. 79. The peak, which occurs in the evening, is due, for the most part, to electric lighting, but the electric elevator requirements usually add an appreciable share to the demand at this time.

135. A Department Store Isolated Plant will have imposed on it a load of the typical properties graphed in Fig. 80. The

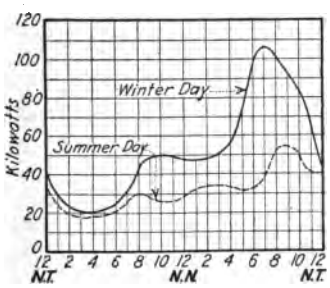


FIG. 79.—Typical graphs of the load on a hotel isolated plant.

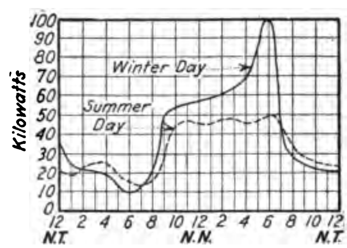


FIG. 80.—Typical graphs of the loads on a department-store isolated plant.

peak occurs quite early in the evening, just about the time the store closes and the demand drops off abruptly after closing time. A somewhat unusual feature which characteristic of department-store loads is that at certain hours of the day the summer off-peak load may be greater than the load imposed at the same hours in the winter time.

136. How the Addition of Off-peak Loads Will Improve the Load Factor is brought out by the graph of Fig. 67. The area A represents the energy required by the regular load imposed on the system or plant in question which operates in a city of approximately 100,000 inhabitants. The graph shows the conditions on Feb. 1, 1916. The load factor for load A is about 59.6 per cent. Now, if the energy, B, required

for the charging of 100 commercial electric vehicles be added during the "valley" the load factor is increased to 63.2 per cent. and a consequent reduction in energy-production cost will result.

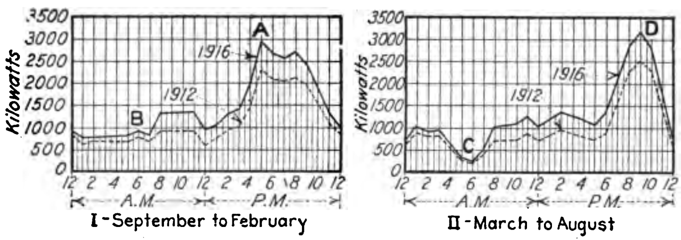


FIG. 81.—A comparison of winter and summer load graphs. The 1912 graphs were plotted from observed data. 1916 graphs were estimated.

137. A Comparison of Winter and Summer Load Graphs for the load imposed on the station in a city of approximately 180,000 inhabitants is given graphically in Fig. 81. This illustration also shows how, in the particular case under con-

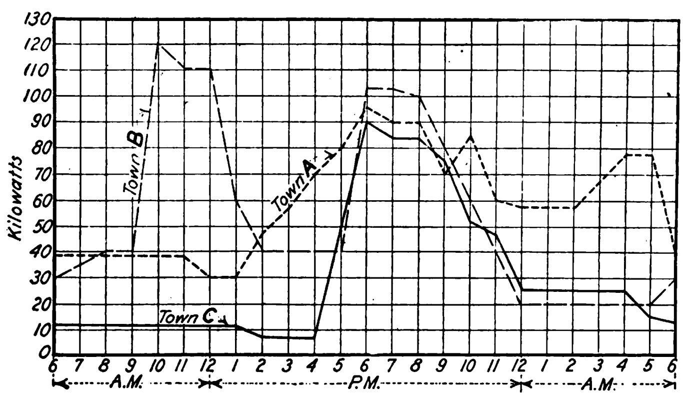


FIG. 82.—24-hour load graphs for three small towns in Georgia. (W. Rawson Collier, Electrical Review, Nov. 13, 1915.)

sideration, the load was increased during the period of 4 years (from 1912 to 1916).

138. The Characteristic Load Graphs for Small Towns may vary considerably as evidenced by the data of Fig. 82, wherein

A, *B* and *C* are the curves for three different municipalities. This condition does not hold in the case of the larger cities, because with them the load graphs for all usually exhibit similar characteristics. All three of the towns (Fig. 82) have approximately 4,800 inhabitants. In all three the water-works pumps are electrically driven. In town *A* during the dry season the motors driving the compressors for the air-lift wells operate during the night and also for several hours in the morning. That is, they operate from 9:00 P.M. to 6:00 A.M. There is a fair consumption of energy for the residential commercial lighting and there is a reasonably good street lighting system.

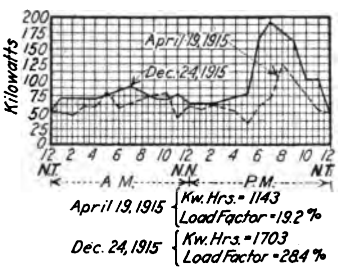


FIG. 83.—Load graphs for a small city central station. (Those shown are for McPherson, Kansas, 4200 population.)

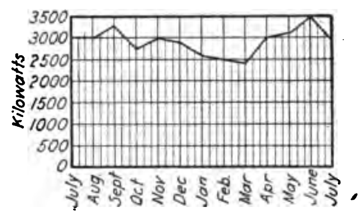


FIG. 84.—Another form of annual load graph. This indicates the monthly load peaks during the year.

The requirements of the town *B* are, in general, similar to those of *A* but in *B* the pneumatic lift water motors are operated from 9:00 A.M. until about 2:00 P.M. In town *C* the water-works pumps are operated between midnight and 4:00 A.M. In instances such as that just described it might be possible to arrange with three different towns which are all fed from the same electricity supply system to operate their water-works motors at such times that the demands imposed by them would not coincide. Where this can be arranged the load factor of the combined load thus imposed may be materially increased. A 24-hr. load graph for another small city of 4,200 population (1910 census), is given in Fig. 83. In this town the morning peak is not as pronounced as it is,

for example, in the graph of Figs. 66 and 77, but there is no decided "valley" at the noon hour period. This indicates the lack of an industrial load; which, if added to this system would, probably, materially increase the load factor.

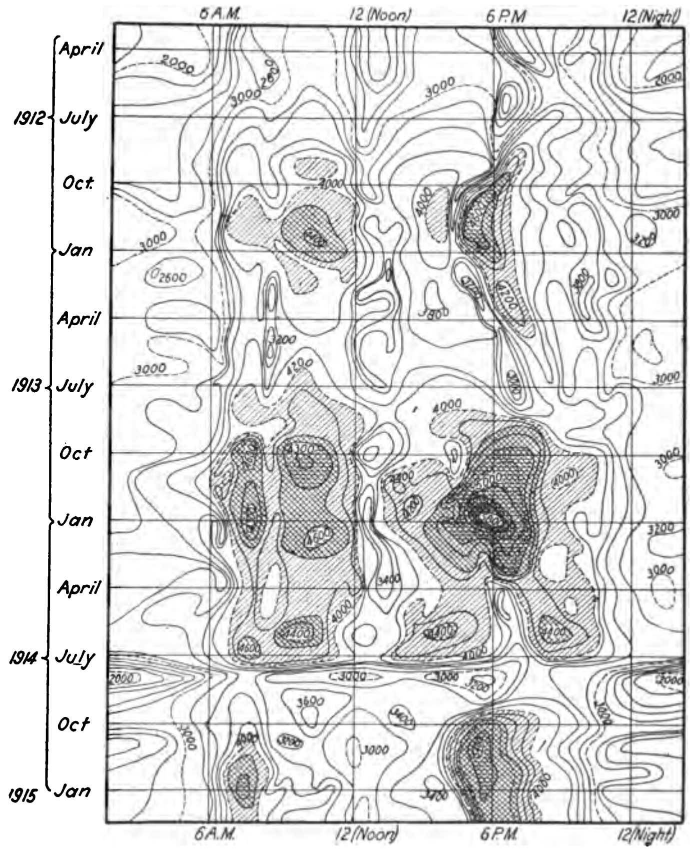


Fig. 85.—A "contour-map" central station load graph.

139. Annual Load Graphs may be plotted as suggested in Figs. 68 and 84 which will indicate how the consumption varies over the entire year. Frequently, such graphs are plotted as in Fig. 84, which indicate the maximum load peak for each

month rather than the variation of power demand throughout the period comprehended by the graph.

140. A "Contour-map" Load Graph is shown in Fig. 85.* In load graphs rendered in accordance with the usual method (see the preceding illustration) the values are ordinarily plotted between *power in kilowatts* and *the hours of the day*—that is to "two dimensions." In the graph of Fig. 85, a third set of values—the days in a year or a series of years—is intro-

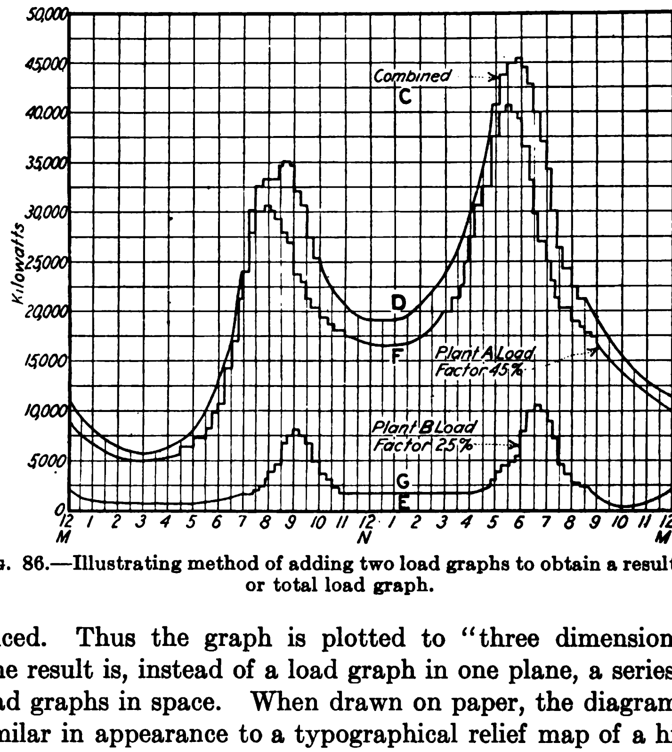


FIG. 86.—Illustrating method of adding two load graphs to obtain a resultant or total load graph.

duced. Thus the graph is plotted to "three dimensions." The result is, instead of a load graph in one plane, a series of load graphs in space. When drawn on paper, the diagram is similar in appearance to a typographical relief map of a hilly locality—or to a weather map which shows the variation of the barometric pressure over a given area. The values plotted in Fig. 85, indicate the kilowatt loads—and the time of the day and the time of the year of their occurrence—on the system of the Company, de Mide de La France. The values near

* Max DuBois in *La Lumiere Electric*, May 8, 1915.

the power contour lines in the graph, which in a typographical map would indicate elevations in feet, indicate the power loads in kilowatts.

NOTE that the total load on the system has increased materially from April, 1913, to January, 1915. The beginning of the great war early in 1914 caused a sudden decrease in the demand for energy, which is clearly indicated by the shading of, and the contour lines on the map. A load graph like this, which is plotted in three dimensions, will forcibly indi-

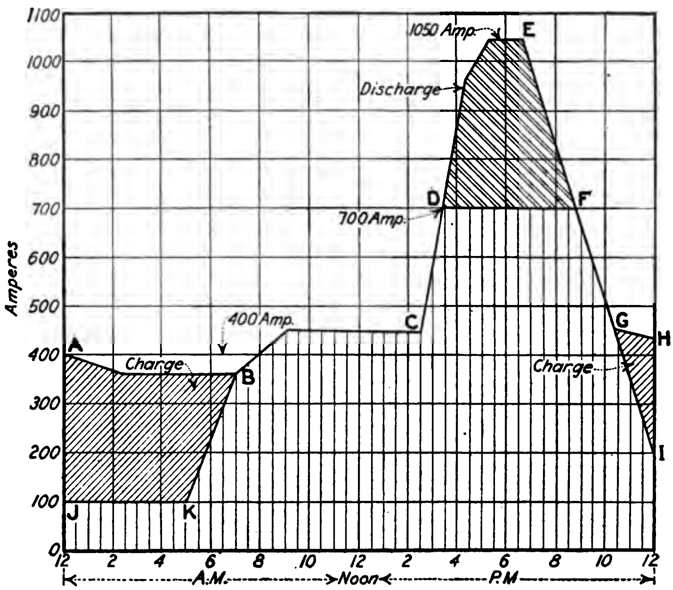


FIG. 87.—Showing how a storage battery may be charged "off peak" and discharged on the "peak" thereby increasing the load factor of the load imposed on generating equipment.

cate not only at which times of the day, but also at what times of the year the energy consumption of the system is small. With this information available, suitable efforts may be made to obtain loads which will "fill in" and "valleys" in the map—not only the daily "valleys" but also the monthly and yearly "valleys"—and thereby increase the overall load factor.

141. The Method of Adding to Load Graphs to obtain their resultant is shown graphically in Fig. 86. Wherein, graphs *A* and *B* are added together giving resultant graph *C*. Thus,

the height of any point in the total graph, C, above the horizontal axis is equal to the sum of the distances of each of the two component graphs above the horizontal axis measured along the ordinate under consideration. Thus, distance $DE = EF + EG$.

142. How a Storage Battery May Be Used for Modifying the Load Demands Imposed on Generating Equipment is illustrated by the load graphs of Fig. 87. With no storage battery the load imposed on the generating equipment is indicated by the graph *JKBCDEFGI* and the load factor is then rather low. But with a storage battery arranged for "off-peak" charging and "on-peak" discharging, the load imposed on the generating equipment would be represented by the graph *ABCDFGH* and the load factor would be relatively high.

SECTION 7

GENERAL PRINCIPLES OF CIRCUIT DESIGN

143. In the Actual Design of Circuits it is not practicable, though it may be entirely possible, to apply Ohm's law unmodified to an extensive circuit. It is, on the contrary, the usual practice to consider only the voltage at the generator or at some assumed source of energy and the current in each portion of the circuit under consideration. From these values the volts drop or loss of potential in the circuit can be readily computed by methods to be described.

NOTE.—It follows from Ohm's law* that the volts drop in any portion of the circuit will equal the product of the resistance of that portion times the current of that portion.

144. The Features Which Should Determine the Sizes of Wires for the Distribution of Electric Energy are three, thus: The wire selected should be of such size: (1) *that it will convey the electrical energy to the location where it is to be utilized without an excessive drop or loss in potential; that is, without excessive* $I \times R$ *drop;* (2) *that the current will not heat it to a temperature which will injure the insulation of the wire or originate a fire;* (3) *that the cost, due to the power loss (the* $I^2 \times R$ *loss) in the wire, caused by the current being forced through the resistance, will not be excessive.*

A conductor may satisfy one of these three conditions and not satisfy the other two, hence, as a general proposition, it is always desirable to examine the conductor size selected for any given condition from the three different standpoints outlined above.

145. The Voltage Drop Will Be Excessive if the Wire Selected Is Too Small.—It may readily be shown* that when a current of electricity flows in a conductor there is always a drop or loss in pressure or voltage. Practically all electrical

* See the author's PRACTICAL ELECTRICITY.

apparatus requires a certain minimum voltage for satisfactory operation. With incandescent lamp circuits it is frequently imperative that the voltage drop be not excessive. The reason is that a small decrease in the voltage impressed on an incandescent lamp causes a great decrease in the light emitted* and a small increase in voltage causes a great decrease in the life of the lamp.

NOTE.—Hence, the voltage regulation of circuits feeding incandescent lamps should be very "close." That is, the allowable voltage drop in incandescent-lamp lighting circuits is small. With circuits supplying motors, a greater drop in voltage can be allowed than on circuits supplying only lamps. However, if the voltage impressed across the terminal of a motor is very much lower than that for which its manufacturer designed the motor, the motor will become excessively hot in operation and may blow its fuses or trip its circuit-breaker.

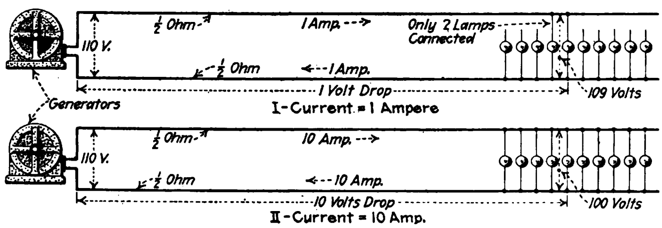


FIG. 88.—Voltage drop in conductors.

146. The Principle of Voltage Drop, sometimes called loss of voltage or drop in potential, is best illustrated by the consideration of the specific example of Fig. 88. The generator serving the circuit is supposed to maintain a pressure of 110 volts at its line terminals. The circuit of Fig. 88 has a total resistance of 1 ohm—½ ohm to each side circuit. Assume that each incandescent lamp connected across the circuit will permit a current of ½ amp. to flow. With only two lamps connected to the circuit, as shown at *I*, the current in the circuit will then be 1 amp. Also the voltage drop in the circuit will (by Ohm's law) be: $1\ amp. \times 1\ ohm = 1\ volt.$ Then the voltage at the lamps would be the voltage impressed on the circuit minus the drop. That is, the voltage at the lamps would be: $110\ volts - 1\ volt = 109\ volts.$

Now with 10 lamps burning, as at *II*, the drop would then

* See the author's AMERICAN ELECTRICIANS' HANDBOOK.

be: 10 *amp.* × 1 *ohm* = 10 *volts.* Then the voltage impressed across the lamps would be: 110 *volts* − 10 *volts* = 100 *volts.* Obviously, with the condition of *I*, the two lamps would have 109 volts impressed across them, whereas with the condition of *II* they would have 100 volts impressed upon them.

147. Incandescent Lamps Cannot be Manufactured Which Will Operate Satisfactorily Over a Wide Range of Voltage.—Hence, the solution of a condition such as that described in the above example would be to use 110-volt incandescent lamps and so proportion the conductor, that with all of the lamps on the circuit burning simultaneously, there would not be more than a volt or two total drop in the entire circuit, instead of 10 volts drop as shown at Fig. 88,*II*. How conductors may be proportioned to thus maintain the drop at a minimum will be described in the material which follows.

148. A Large Voltage Drop in a Conductor Also Indicates a Large Power Loss in That Conductor.—It is often, from a standpoint of economics, advisable to use a conductor of such large size that the voltage drop in it will be much less than that necessary to maintain the voltage at the receiving apparatus up to the value absolutely required. The reason why the use of such large conductors is frequently advisable is so that the power loss in them will not be excessive. This situation is considered more in detail later.

149. In Incandescent-lamp Circuits the Voltage Drop Allowable varies somewhat with the character of the apparatus supplied and with other conditions. Where the incandescent lamps operate at a pressure of 110 volts or thereabouts, the circuit conductors should be so proportioned in a first-class installation, that the pressure at the lamps will, under no condition in normal operation, vary more than 3 volts. That is, on this basis the maximum permissible voltage drop is 3 volts. Frequently, however, a variation of 4 volts is permitted. Where the electrical energy is generated in the building, the entire 3 or 4 volts drop can then occur in the conductors within the building. Where the energy is generated by a central station, it is usually customary, with 110-volt circuits, to allow 2 volts drop in the conductors within the building and assume that there will be 1 or 2 volts drop, or the equivalent

thereof, in the conductors between the buildings and the central generating station.

NOTE.—A number of central-station companies will not connect 110-volt installations where the voltage drop from the point of entrance to the most remote lamp in the inside wiring installation exceeds 2 volts. A few companies limit the drop in the inside wiring installation to 1 volt. Sometimes, in isolated installations, where energy is produced at low cost, a 5-volt drop is allowed on 110-volt incandescent-lamp circuits but the results are not wholly satisfactory. A 5-volt drop is certainly the upper limit for a 110-volt incandescent-lamp circuit. While the values above enumerated apply specifically to 110-volt lamp circuits, they can be used proportionately for lamp circuits operating at other voltages. Drop is often expressed as a percentage, thus: The total drop on a circuit feeding incandescent lamps should never exceed 5 per cent. of the lamp voltage.

150. A Greater Drop Is Permitted in Motor Circuits than in lamp circuits because motors are not so sensitive to variation of voltage. With motors a drop exceeding 10 per cent. of the receiver voltage is seldom advisable and it is usually best, considered from a standpoint of operation, to allow a drop not in excess of 5 per cent. If motors and incandescent lamps are served by the same circuit the drop in it should be limited to about 3 per cent.

151. The Apportionment of Voltage Drop Among the Different Components of the Circuit will now be considered. In circuit design it is necessary to apportion or distribute the total drop which has been allowed in the entire circuit between the feeders, mains, sub-mains and branches. In incandescent lighting, most of the drop is confined to the feeders because, if there is excessive drop in the mains and branches, lamps located close together, but served by different mains and branches, might operate at decidedly different brilliancies. With an isolated plant where energy is generated on the premises, a total drop of 3 volts (for 110-volt circuits) may be apportioned thus: branches, 1 volt; mains, one-third of the remainder; feeders, two-thirds of the remainder. This will give an actual drop of 1 volt in the branches, 0.66 volt in the mains and 1.33 volts in the feeders.* Where the premises is served by a central station, the practice of the utility concern may allow 2 volts drop in its secondary mains and the

* See table in author's AMERICAN ELECTRICIANS' HANDBOOK.

service to the premises. In such a case the total drop within the premises should not exceed 1 to 2 volts. Where a utility company is to give service, it should be consulted regarding its practice in this respect. Some central-station companies require that the voltage drop in interior wiring installations which they are to serve should not exceed a certain maximum. In any case it is frequently the practice to allow 1 volt drop for the branches and to apportion the remainder of the available drop to the main circuits and feeders.

152. The Apportionment of Drop on 2,400-volt Distribution Systems is often made under the assumption that the secondary voltage of the transformers remains practically constant. This will be found true in a well-laid-out system, particularly if automatic feeder regulators are used.

152A. The Apportionment of Drop in Motor Circuits may be made on the basis that 1 volt will be allowed in the branches, two-thirds of the remaining drop in the mains and one-third for the feeders. Most of the drop should be confined to the mains in order that a variation in load of one motor of the group will affect the others as little as possible. Where motor circuits are fed by transformers it is usually assumed that the voltage at the secondary side of the transformers remains practically constant. Therefore, all of the al'owable drop is apportioned to the secondary circuit. Where a group of motors is fed by a main circuit and branches, the drop in the branches, if they are not too long, is frequently 1 volt or less, under normal working conditions. The reason for this is because the *National Electrical Code* rules require that a branch conductor serving a motor be capable of safely carrying a current 25 per cent. greater than the normal full-load current of the motor.

153. The Safe-current-carrying Capacity of Wires Should Always Be Considered When Designing Circuits.—A conductor may have ample cross-sectional area to convey current a given distance with a sufficiently small drop in voltage but yet may be so small that it will overheat. After a wire has been selected with reference to voltage drop, the safe-current-carrying capacity table (Table 154) should be consulted, and if the wire first selected is not large enough to safely carry the current in accordance with the value specified

in Table 154, a wire that *is* large enough, on the basis of Table 154 values, should be used.

154. Allowable Carrying Capacities of Wires.—These values are taken from the *National Electrical Code,* Rule 18.

B. & S. gage number	Diameter of solid wire in mils	Area in circular mils	Table *A*, rubber insulation, amperes	Table *B*, other insulation, amperes
18	40.3	1,624	3	5
16	50.8	2,583	6	10
14	64.1	4,107	15	20
12	80.8	6,530	20	25
10	**101.9**	**10,380**	**25**	**30**
8	128.5	16,510	35	50
6	162.0	25,250	50	70
5	181.9	33,100	55	80
4	204.3	41,740	70	90
3	**229.4**	**52,630**	**80**	**100**
2	257.6	66,370	90	125
1	289.3	83,690	100	150
0	325.0	105,500	125	200
00	364.8	133,100	150	225
000	**409.6**	**167,800**	**175**	**275**
....	.....	200,000	200	300
0000	460.0	211,600	225	325
		300,000	275	400
		400,000	325	500
		500,000	**400**	**600**
		600,000	450	680
		700,000	500	760
		800,000	550	840
		900,000	600	920
		1,000,000	**650**	**1,000**
		1,100,000	690	1,080
		1,200,000	730	1,150
		1,300,000	770	1,220
		1,400,000	810	1,290
		1,500,000	**850**	**1,360**
		1,600,000	890	1,430
		1,700,000	930	1,490
		1,800,000	970	1,550
		1,900,000	1,010	1,610
		2,000,000	**1,050**	**1,670**

1 mil = 0.001 in.

155. Calculations for Voltage Drop Are Usually Based on the Resistance of a Circular Mil-foot of Commercial Copper Wire as copper is the only metal used to any extent for the distribution of electrical energy. It can be shown that the resistance of any conductor of circular cross-section may be computed from the formula:

$$R = \frac{p \times l}{d^2} \qquad \text{(ohms)} \tag{40}$$

Wherein: R = the resistance of the conductor, in ohms. p = the resistivity, in ohms per circular mil-foot, of the metal composing the conductor. l = the length of the conductor, in feet. d = the diameter of the conductor in 0.001 in.

156. In Practical Wiring Calculations the Resistance of a Circular Mil-foot of Copper May Be Taken as 11 Ohms* and since d^2 = the diameter of the conductor, in 0.001 in. squared, that is d^2 = the sectional area in circular mils, the above formula (40) becomes:

$$R = \frac{11 \times l}{cir.\ mils} \qquad \text{(ohms)} \tag{41}$$

$$l = \frac{cir.\ mils \times R}{11} \qquad \text{(feet)} \tag{42}$$

$$cir.\ mils = \frac{11 \times l}{R} \qquad \text{(circular mils)} \tag{43}$$

Wherein: All of the symbols have the meanings specified above.

157. The Drop or Loss of Voltage in Any Conductor can be most conveniently computed by using the Ohm's law formula, which has been so modified that the expression for resistance given in equation (41) above is used. Thus, from Ohm's law:*

$$V = I \times R \qquad \text{(volts)} \tag{44}$$

Wherein: V = the drop, in volts, in a given conductor. I = the current, in amperes, in that conductor. R = the resistance, in ohms, of the conductor. Since, however, formula (41)

* See the author's AMERICAN ELECTRICIANS' HANDBOOK.

above also gives an expression for R, it can be substituted in formula (44) above with this result:

$$V = I \times R = \frac{I \times 11 \times l}{cir.\ mils} \quad \text{(volts)} \tag{45}$$

$$V = \frac{I \times 11 \times l}{cir.\ mils} \quad \text{(volts)} \tag{46}$$

$$I = \frac{cir.\ mils \times V}{11 \times l} \quad \text{(amperes)} \tag{47}$$

$$l = \frac{cir.\ mils \times V}{11 \times I} \quad \text{(feet)} \tag{48}$$

$$cir.\ mils. = \frac{I \times 11 \times l}{V} \quad \text{(circular mils)} \tag{49}$$

Note that the symbol l in the above equations stands for the double distance of the circuit. That is, the entire length

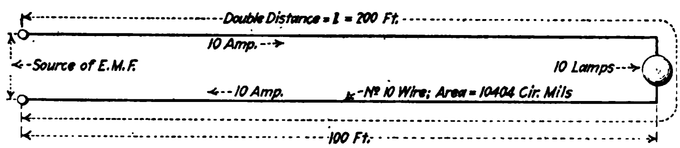


FIG. 89.—Illustrating double distance.

of the circuit, in feet, is shown in Fig. 89. See the following example.

EXAMPLE.—The drop in the circuit of Fig. 89, with a current of 10 amp. flowing in the circuit, which is 200 ft. long and of No. 10 wire (area is 10,380 cir. mils, see Table 154) will be, substituting in formula (46):

$$V = \frac{I \times 11 \times l}{\text{cir. mils}} = \frac{10 \times 11 \times 220}{10{,}380} = 2.1 \text{ volts.}$$

That is, the total drop in the circuit of Fig. 89, with a current of 10 amp. flowing, is 2.1 volts.

158. To Compute the Voltage Drop in a Lighting or Power Circuit, a modified form of equation (46) is most convenient. Since, in actual installations, the two side wires of any circuit follow about the same course and are each of about the same

length, it is desirable to use the single distance (see Fig. 90) designated by the symbol L rather than the double distance, designated by the symbol l. Now, l (as is obvious from Figs. 89 and 90) equals $2 \times L$. Therefore, substituting $2 \times L$ for l in equation (46) we have:

$$(50) \qquad V = \frac{I \times 11 \times 2 \times L}{cir.\ mils} \qquad \text{(volts)}$$

However, since the values of "11" and "2" would always appear in the formula it is convenient to multiply them together once for all and then to use the value of "22" in the

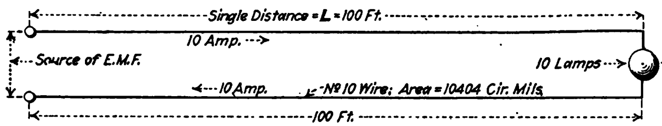


FIG. 90.—Illustrating single distance.

formula instead of "11×2." Hence, from (50), the working formula now becomes:

$$(51) \qquad V = \frac{I \times 22 \times L}{cir.\ mils.} \qquad \text{(volts)}$$

$$(52) \qquad I = \frac{V \times cir.\ mils}{22 \times L} \qquad \text{(amperes)}$$

$$(53) \qquad L = \frac{cir.\ mils. \times V}{22 \times I} \qquad \text{(feet)}$$

$$(54) \qquad cir.\ mils = \frac{22 \times I \times L}{V} \qquad \text{(circular mils)}$$

Wherein: V = the drop or loss of potential, in volts, in the circuit under consideration. I = the current, in amperes, in the circuit under consideration. L = the single distance, Fig. 90, of the circuit under consideration. *Cir. mils* = the area of the conductor of the circuit, in circular mils, as shown in Table 154.

EXAMPLE.—What is the voltage drop in the circuit of Fig. 90? The current, I, is 10 amp.; the single distance, L, is 100 ft. and the conductor is of No. 10 wire. Now, a No. 10 wire has, from Table 154, an area of

10,380 cir. mils. SOLUTION.—Substituting in formula (51): $V = (I \times 22 \times L) \div cir.\ mils = (10 \times 22 \times 100) \div 10{,}380 = (22{,}000 \div 10{,}380) = 2.1$ *volts*. Therefore, the drop in the circuit of Fig. 90 is 2.1 volts. Observe that this is the same result that was obtained with the other form (46) of the formula in the example given in connection with Fig. 89. Both examples, obviously, show solutions of the same problem but in the first the double distance l was used and in the second the single distance L. Other examples are given in the following paragraphs.

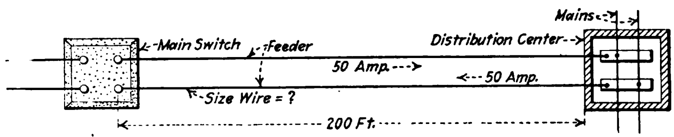


FIG. 91.—Finding size of wire.

159. To Find the Size Wire for a Circuit When the Current, Length of Circuit and Allowable Drop are Known (this relates specifically to direct current two-wire circuits) it is, obviously, merely necessary to substitute the known values in equation (54) given above.

EXAMPLE.—What size wire (Fig. 91) could be used for a feeder to carry a current of 50 amp. from the main switch to a distribution center 200

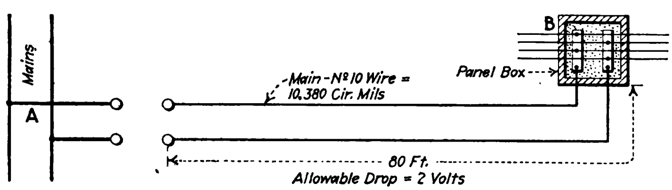


FIG. 92.—Circuit from main to panel box.

ft. distant measured along the circuit. The allowable drop is 2 volts. SOLUTION.—Substitute in equation (54) thus: $Cir.\ mils = (22 \times I \times L) \div V = (22 \times 50 \times 200) \div 2 = (220{,}000 \div 2) = 110{,}000$ *cir. mils*. Now, referring to Table 154; the next standard size wire larger than 110,000 cir. mils is No. 00 (which has an area of 133,100 cir. mils). Hence, No. 00 wire should be used.

160. To Find the Current in a Circuit That Will Cause a Given Drop in a Given Wire of Known Length (this relates specifically to direct-current two-wire circuits) formula (52) may be utilized as shown in the following example.

EXAMPLE.—What is the greatest current that can be carried by the circuit of Fig. 92, which extends from a main, A, to a panel box, B, 80 ft. distant, with an allowable drop of 2 volts? The wire is No. 10 which has (see Table 154) an area of 10,380 cir. mils. SOLUTION.—Substitute in formula (52) above thus: $I = (cir.\ mils \times V) \div (22 \times L) = (10{,}380 \times 2) \div (22 \times 80) = (20{,}760 \div 1{,}760) = 11.8\ amp.$ Therefore, no current greater than 11.8 amp. could be carried by the No. 10 wire circuit of Fig. 92 without causing a drop greater than 2 volts.

161. To Find the Length Circuit That Will Carry a Known Current Over a Conductor of Known Size With a Given Drop (this relates specifically to direct-current two-wire circuits)

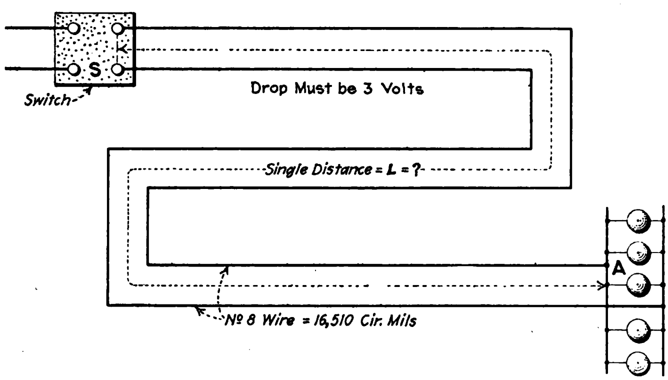


FIG. 93.—Arranging circuit to have a given drop.

equation (53) may be utilized as shown in the following example.

EXAMPLE.—Some No. 8 copper wire having (from Table 154) an area of 16,510 cir. mils. is available. It is desired that just enough of it be used that the drop in it shall be 3 volts when a current of 30 amp. is forced through it. The wires are to be arranged between a switch and a group of lamps as shown in Fig. 93. How many feet of *circuit* must be inserted between the switch, S, and the lamps, A? SOLUTION.—Substitute in formula (53) thus: $L = (cir.\ mils \times V) \div (22 \times I) = (16{,}510 \times 3) \div (22 \times 30) = (49{,}530 \div 660) = 75\ ft.$ (almost). The length of the circuit, single distance, would be 75 ft. but the length of wire required, double distance, would be 150 ft.

162. The Formula for Figuring the Power Loss in Any Conductor, Either Alternating-current or Direct-current,

may easily be derived from what has preceded. It can be shown:*

$$P = I^2 \times R \qquad \text{(watts)} \tag{55}$$

Now, from equation (41): $R = (11 \times l) \div cir.\ mils$. Then substituting this value for R in formula (55) the result is:

$$P = I^2 \times \frac{11 \times l}{cir.\ mils} \qquad \text{(watts)} \tag{56}$$

Wherein.—P = the power lost in the conductor, in watts. I = the current, in amperes in the conductor. l = the length (double distance) of the conductor, in feet. *Cir. mils* = the area of the conductor, in circular mils.

163. The Formula for Computing the Power Loss in Any Direct-current Two-wire Circuit (the formula also applies for a single-phase alternating-current circuit) follows from equation (55) above and the fact that (see Figs. 89 and 90) double distance equals twice single distance. Thus:

$$P = \frac{I^2 \times 2 \times 11 \times L}{cir.\ mils} = \frac{22 \times I^2 \times L}{cir.\ mils} \qquad \text{(watts)} \tag{57}$$

hence,

$$I = \sqrt{\frac{P \times cir.\ mils}{22 \times L}} \qquad \text{(amperes)} \tag{58}$$

$$L = \frac{cir.\ mils \times P}{22 \times 1^2} \qquad \text{(feet)} \tag{59}$$

$$cir.\ mils = \frac{22 \times I^2 \times L}{P} \qquad \text{(circular mils)} \tag{60}$$

Wherein.—All of the symbols have the meanings hereinbefore specified except that P = the power expended in the circuit in watts and L = the single distance of the circuit, in feet.

164. The Determination of the Loads That Will be Carried by the Conductors is the first operation that should be performed in making wiring calculations for any wiring installation, large or small. Where an installation of any consequence is to be figured, blue prints are furnished and on these the loads, in amperes, that will be imposed on the different conductors

* See the author's PRACTICAL ELECTRICITY.

can be indicated in pencil. If no plans are furnished it will usually be found profitable, even if the installation is small and simple, to make a pencil sketch of the wiring layout and note on it the load, in amperes, that the conductors must carry. It is usually most convenient to reduce the loads from horse-power, watts, etc., into corresponding ampere values.

Note.—Where the loads are thus reduced to amperes, the equivalent values are available for substitution in the formulas for computing wire sizes. Furthermore, it is necessary, in nearly every case, to know the current each conductor will carry, so that one can be certain that the conductor is sufficiently large to safely carry it. The currents taken by arc and incandescent lamps and motors of the different types and capacities will be found in tables given in the author's American Electricians' Handbook.

165. In Noting the Ampere Loads on a Wiring Plan, commence with the branches and if the receivers on the branches are of several different capacities, indicate opposite each the current it takes. Then, total the current values of each branch and note this final total at the point where the branch joins the larger conductor which feeds it. Place a circle around the total value to show it is the total. If all of the receivers on a branch are of the same capacity the aggregate load can be readily totaled without indicating the load at each receiver. If there is a probability of the addition of future receivers, indicate that they are "future" with the letter "F."

166. National Electrical Code Rules Require That Motor Branch Circuits be of sufficiently large wire that they will safely carry a current 25 per cent. greater than the normal current of the motor. This has, however, nothing to do with the voltage drop on mains and feeders, so the normal full-load current of each motor is noted on the plan and the normal motor currents are added to get the total current values. It is often convenient to note a current 25 per cent. greater than the full-load current, in a square near each motor branch, so that the wire used in the branch can be readily checked for carrying capacity.

167. The Symbol L in the Formulas Stands for the Distance in Feet to the Load Center of the Circuit.—This distance will

be the actual length if the load is concentrated at the end or it will be the distance to the "center of gravity"* if the load is distributed. When found, this distance is used as the length of the circuit and is substituted for the letter L in the formula.

168. In Measuring Plans a convenient scale can be made by dividing, with pencil lines, a strip of drawing paper, possibly 30 in. long, into "feet" divisions, to the same scale as that of the drawing under consideration. The number of feet represented by each mark is indicated by the numeral opposite the mark. In use, the 0 mark at one end of the scale is placed opposite the starting point of the circuit and the paper strip is laid along the circuit. The length of the circuit, unless it is too long, is then read directly from the strip. Such paper strips are very convenient, because they are cheap, light and easily handled and they can be bent to follow contours of circuits having irregular courses.

* See the author's AMERICAN ELECTRICIANS' HANDBOOK, under the heading "Load Center."

SECTION 8

CALCULATION AND DESIGN OF DIRECT-CURRENT CIRCUITS

169. Direct-current Circuit Conductors are most conveniently calculated from formula (54). The examples given under the following paragraph illustrate the application of this equation.

170. The Calculation of a Direct-current Two-wire Current can be best explained by the consideration of numerical

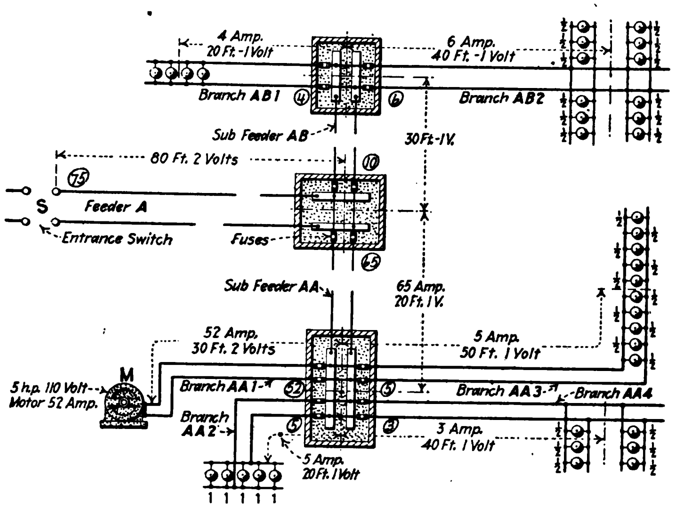


FIG. 94.—Wire sizes for an installation.

examples. One problem showing how the wire size for a feeder may be calculated was given in connection with Fig. 91.

EXAMPLE.—What size wire should be used for a branch circuit in which the allowable drop is 1 volt; the current is 10 amp. and the distance from the start of the circuit to the load center is 60 ft.? SOLUTION.—Substitute in formula (54) thus: *Cir. mils* = $(22 \times I \times L) \div V = (22 \times 10$

$\times$ 60) $\div$ 1 = (13,200 *cir. mils*. Now refer to Table 154: a 13,200-cir. mil conductor is larger than a No. 10 wire and smaller than a No. 8. As a rule, the next larger size should be selected; therefore, No. 8 wire (which with rubber insulation will safely carry 35 amp.) will be used.

EXAMPLE.—In Fig. 94 is shown a diagram of a distribution installation. The wire sizes for each circuit will be computed below. The length of each circuit, or the distance to its load center, is indicated above the circuit and the allowable drop in volts in each circuit is shown with the length. The total drop allowed from the entrance switch, S, to the last lamp on any circuit is 4 volts. However, the total drop allowed to the motor, M, is 5 volts. The current, in amperes, taken by each receiver (consuming device) is indicated opposite the receiver and the total ampere load of each circuit is indicated at the starting point of the circuit within a circle. Each circuit is designated by a letter or group of letters. Each component will be considered separately. SOLUTION.—It will be assumed that all of the conductors will have rubber insulation; therefore, their current-carrying capacities will be determined by the values given in column A of Table 154.

BRANCH AB_1.

Load 4 amp.; distance, 20 ft.; drop, 1 volt. Substitute in formula (54): $Cir.\,mils = (22 \times I \times L) \div V = (22 \times 4 \times 20) \div 1 = 1{,}760$ *cir. mils*.

Now referring to Table 154, the standard size wire next larger than 1,760 cir. mils is No. 16, which has an area of 2,583 cir. mils. This size wire would be satisfactory were it not for the fact that the *National Electrical Code* prohibits the use of any wire smaller than No. 14. Hence, No. 14 must be used in this case. (In outdoor service no copper wire smaller than No. 8 or No. 6 has sufficient mechanical strength to give satisfactory service.) No. 14 rubber insulated wire has a safe current-carrying capacity of 15 amp. hence, is amply large to carry the 4 amp. load in circuit AB_1.

BRANCH AB_2.

Load, 6 amp.; distance, 40 ft.; drop, 1 volt. Substitute in formula (54): $Cir.\,mils = (22 \times I \times L) \div V = (22 \times 6 \times 40) \div 1 = 5{,}280$ *cir. mils*. Referring to Table 154, the next larger size wire is No. 12 which has an area of 6,530 cir. mils and since it has a current-carrying capacity of 20 amp. will readily carry the 6 amp. of circuit AB_2. Therefore, No. 12 is satisfactory and should be used.

SUB-FEEDER AB.

Load, 10 amp.; distance, 30 ft.; drop, 1 volt. Substitute in formula (54): $Cir.\,mils = (22 \times I \times L) \div V = (22 \times 10 \times 30) \div 1 = 6{,}600$ *cir. mils*. Use No. 10 wire, which has an area of 10,380 cir. mils and which will safely carry 24 amp.

BRANCH AA_1.

Load, 52 amp. (see Table in AMERICAN ELECTRICIANS' HANDBOOK

for currents taken by motors of different horse-power voltage); distance, 30 ft.; allowable drop, 2 volts. Substitute in the formula (54): *Cir. mils* = $(22 \times I \times L) \div V = (22 \times 52 \times 30) \div 2 = (34{,}320 \div 2) =$ 17,160 *cir. mils*. Referring to Table 154, No. 6 wire, which has an area of 26,250 cir. mils, is the next largest size. This wire would carry the current of the motor with much less than 2 volts drop. However, since it is specified in the *National Electrical Code* that branch circuits to motors must be capable of safely carrying a current at least 25 per cent. greater than the normal full-load current of the motor, a wire must be selected that will safely carry: $52 \times 1.52 = 65$ *amp.* Therefore, No. 4 wire must be used for this branch, which will safely carry 70 amp.

BRANCH AA_2.

Load, 5 amp.; distance, 20 ft.; drop, 1 volt. Substitute in the formula (54): *Cir. mils* = $(22 \times I \times L) \div V = (22 \times 5 \times 20) \div 1 = 2{,}200$ *cir. mils*. In Table 154 it is shown that the area of a No. 16 wire is 2,583 cir. mils so this size would be satisfactory insofar as drop in voltage is concerned. However, as above outlined, wires smaller than No. 14 are not permitted in ordinary wiring. Hence, No. 14 must be used. No. 14 will safely carry 15 amp., hence is amply safe for the 5 amp. load of branch AA_2.

BRANCH AA_3.

Load, 5 amp.; distance, 50 ft.; drop, 1 volt. Substitute in the formula (54): *Cir. mils* = $(22 \times I \times L) \div V = (22 \times 5 \times 50) \div 1 = 5{,}500$ *cir. mils*. Again referring to Table 154, a No. 12 wire, which is plenty large enough to carry the current, should be used.

BRANCH AA_4.

Load, 3 amp.; distance, 40 ft.; drop, 1 volt. Substitute in formula (54): (*Cir. mils*) = $(22 \times I \times L) \div V = (22 \times 3 \times 40) \div 1 = 2{,}640$ *cir. mils*. By consulting Table 154 it is found that a No. 14 wire should be used.

SUB-FEEDER AA.

Load, 65 amp.; distance, 20 ft.; drop, 1 volt. Substitute in formula (54): *Cir. mils* = $(22 \times I \times L) \div V = (22 \times 65 \times 20) \div 1 = 28{,}600$ *cir. mils*. Now, referring to Table 154, No. 5 wire, which has an area of 33,100 cir. mils, would satisfy the conditions as to drop. However, on sub-feeder AA, is, as indicated in Fig. 94, 65 amp. Therefore, it would be necessary to use a No. 4 conductor which has a safe current-carrying capacity (Table 154) of 70 amp. Furthermore, it should be noted that it was necessary to use No. 4 wire for branch AA_1. Therefore, a wire at least as large as No. 4 wire will probably be required for sub-feeder AA. In some localities the inspector might require the installation of No. 3 for sub-feeder AA.

FEEDER A.

Load, 75 amp.; distance, 80 ft.; drop, 2 volts. Substitute in formula (54): *Cir. mils* = $(22 \times I \times L) \div V = (22 \times 75 \times 80) \div 2 = 66{,}000$

cir. mils. By referring to Table 154 it is evident that a No. 2 wire, which has an area of 66,370 cir. mils, may, since it will safely carry 90 amp. (the load is but 75 amp.) be used.

EXAMPLE.—What size wire should be used for the line shown in Fig. 95, which supplies a 40-h.p., 220-volt motor? The normal current of this motor, as obtained from a table of motor currents, is 150 amp. All of the wiring is assumed to be supported on a pole line or exposed. Hence, weather-proof insulated copper wire will be used on the pole line and slow-burning insulated wire within the buildings. SOLUTION.—Load, 150 amp.; distance, 500 ft.; allowable drop $= 0.044 \times 220 = 10$ *volts*, approximately. Substitute in formula 54: *Cir. mils* $= (22 \times I \times L) \div V = (22 \times 150 \times 500) \div 10 = 1,650,000 \div 10 = 165,000$ *cir. mils*. Referring to Table 154, the next largest standard size wire is No. 000, which has an area of 167,000 cir. mils and will safely carry 272 amp. with either slow-burning or weather-proof insulation. Hence, No. 000 is the wire size that should be used.

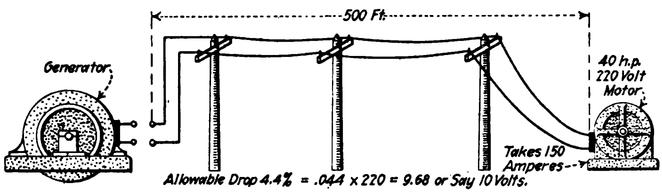


FIG. 95.—Size wire for motor line.

171. The Calculations for Direct-current Three-wire Circuits are made in essentially the same manner as are those for direct-current two-wire circuits. With the "balanced" three-wire circuits no current flows in the neutral wire. In practice circuits should be very nearly balanced and in making wiring calculations it is usually assumed that they are balanced unless there is obviously a great unbalance.

172. The Process in Determining Conductor Sizes for Three-wire Circuits is about as follows: The first step is to ascertain the current which will flow in the outside wires. This value is obtained in practice by adding together the currents taken by all of the receivers which are connected between the neutral and the outside wires and divide the sum by 2, as indicated in Fig. 96. Then, to this value are added the currents taken by the receivers, if there are any, which are connected across the outside wires. The sum of these values

is then taken as the total current. The computation is then made by the same method as for any two-wire circuit. The neutral wire is ordinarily disregarded in the calculation because it is usually assumed that it carries no current. The

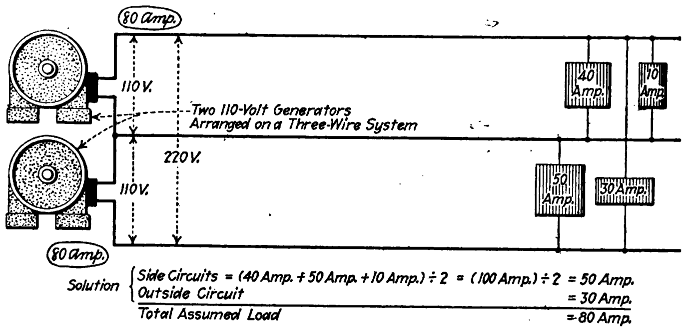


FIG. 96.—Illustrating how the ampere load on an unbalanced three-wire circuit may be estimated.

neutral may* be made smaller than the outside wires but is frequently made of the same cross-sectional area. The drop, V, in the formula is the drop in the outside wires and is two

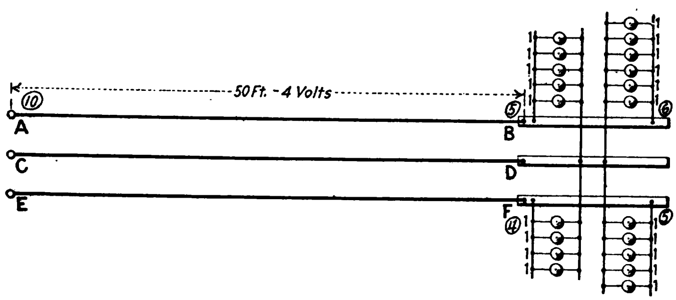


FIG. 97.—Size wire for three-wire main.

times the drop of each receiver between the neutral and an outside wire.

EXAMPLE.—What size wire should be used for the three-wire sub-feeder of Fig. 97. Allowable drop is 4 volts, length of sub-feeder, 50 ft. and total 110-volt load 20 amp. SOLUTION.—Although the load is not balanced on

* See the author's AMERICAN ELECTRICIANS' HANDBOOK.

the two sides of the circuit, it would be assumed in practical wiring calculations that it is balanced. Actually, with the loads as shown in Fig. 97, 11 amp. would flow in the upper outside wire, AB, 9 amp. in the lower outside wire, EF and 2 amp. in the neutral, CD. In practice, it would be assumed that one-half of the total load (between neutral and outside wires), or $(5 + 6 + 4 + 5) \div 2 = 10$ amp., would flow in each outside wire. Hence: load, 10 amp.; distance, 50 ft.; drop, 4 volts. Substitute in formula (54): $Cir.\ mils = (22 \times I \times L) \div V = (22 \times 10 \times 50) \div 4 = 2{,}750\ cir.\ mils$. From Table 154 it is evident that the next larger size than one having 2,750 cir. mils area is a No. 14 which has an area of 4,107 cir. mils and which will safely carry 12 amp. Hence, No. 14 is the wire to use.

173. The Actual Voltage Drop in an Unbalanced Three-wire Circuit may be calculated by using the formula (46). The operation will be illustrated with an example.

EXAMPLE.—Consider a circuit loaded as shown in Fig. 98. The circuit is 373 ft. long, each of the conductors is of No. 14 wire (area, 4,107 cir. mils) and the load is unbalanced, the receivers on one side of the circuit taking 10 amp. while those on the other side take only 1 amp. What is the voltage drop in the conductors and what is the voltage at the receivers? SOLUTION.—The current in each wire is, obviously, that indicated in Fig. 98. To find the drop in volts in each wire, substitute in formula (46) thus:

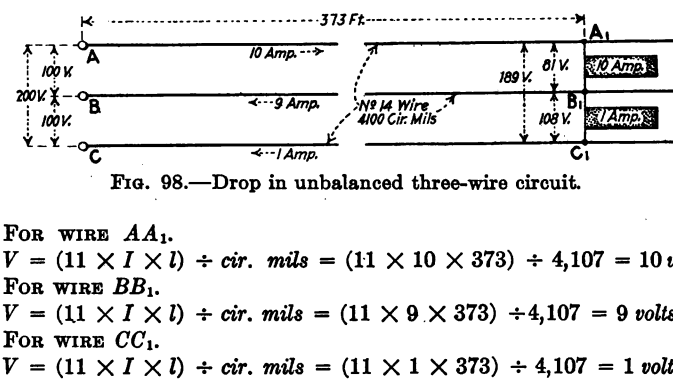


FIG. 98.—Drop in unbalanced three-wire circuit.

FOR WIRE AA_1.
$V = (11 \times I \times l) \div cir.\ mils = (11 \times 10 \times 373) \div 4{,}107 = 10\ volts.$
FOR WIRE BB_1.
$V = (11 \times I \times l) \div cir.\ mils = (11 \times 9 \times 373) \div 4{,}107 = 9\ volts.$
FOR WIRE CC_1.
$V = (11 \times I \times l) \div cir.\ mils = (11 \times 1 \times 373) \div 4{,}107 = 1\ volt.$

The voltage across the two outside wires A_1C_1 at the end of the circuit is obtained by subtracting the sum of the drops in the two outside wires from the impressed voltage, thus: $200 - (10 + 1) = 200 - 11 = 189$ *volts*. Therefore, 189 volts is the pressure across the two outside wires at the end of the circuit. The voltage at the end of the circuit between

the neutral and the upper outside wire is (see Fig. 98) 81 volts and the pressure between the neutral and the lower outside wire is 108 volts. The method of obtaining these voltages will be made clear by a consideration of Fig. 99 which illustrates the same general problem as Fig. 98 and which is further discussed in a following article.

174. To Insure That Three-wire Circuits Will Be Balanced as Nearly as Is Feasible, the lamps and other devices served by the circuit should be divided between the two sides of the system so that the load on the two side circuits will be equal, for full capacity or for any fraction thereof. For this reason,

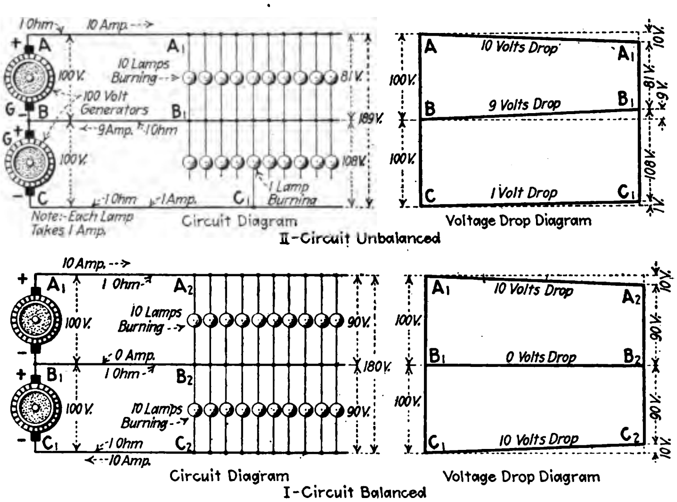


FIG. 99.—Effect of unbalance on a three-wire circuit.

three wires should be carried to any location where a considerable amount of energy is required. Three wires should be carried to every building in the case of an outdoor distribution and to every distribution center in the case of distribution between buildings. In case many lamps are to be lighted at the same time they should, preferably, be controlled by three-way switches.

NOTE.—Although every precaution may be taken to insure equal loading on the two side circuits, it is possible that the balance cannot be maintained in practice. For example, it may occur that a great many

lamps are lighted on one side circuit of a three-wire system and very few on the other side. In the event of such a contingency the drop in voltage would be about twice its normal value on the side circuit having the larger number of lamps connected to it and the voltage across the lamps feeding from that side circuit would be correspondingly decreased. Simultaneously, the voltage across the lamps on the other side circuit might be raised. See Fig. 99, which shows an exaggerated example. The probability of a condition such as that outlined in Fig. 99,*II* is, particularly in large systems, remote.

175. It is Not Sufficient in a Three-wire System to Have Equal Numbers of Lamps on the Two Sides.—They should also be distributed in approximately the same manner. What

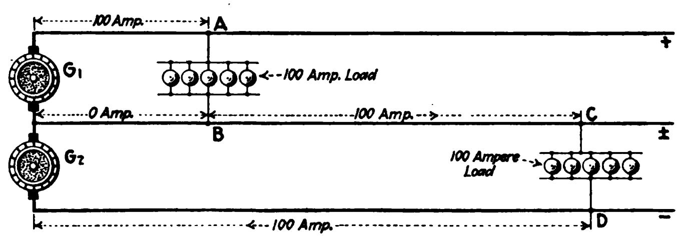


FIG. 100.—Effect of nonuniformly-distributed load.

may occur if the distribution of the lamps is not systematical is indicated in the following example.

EXAMPLE.—With a group of lamps requiring 100 amp. (Fig. 100) connected between the + and the − wire at one point, *AB*, and an equal connection between the neutral and the − wire, at the location *CD* some distance away, there would be a current of 100 amp. flowing in the neutral wire between point *B* and *C*. This heavy current in the neutral would involve considerable extra drop although the system would at the generating station appear to be operating in perfect balance. In practice, this local unbalancing of the three-wire system is one of the chief causes of variation of voltage. Hence, the possibility of its occurring should be minimized by intelligently distributing this load on both the side circuits of the system. It is because of this possibility that it is desirable to carry the three wires to every location where considerable amount of energy is required.

SECTION 9

CALCULATION AND DESIGN OF ALTERNATING-CURRENT CIRCUITS

176. There Are Certain Factors Which Affect the Computation of Alternating-current Circuits which are not encountered with direct-current circuits. The phenomena to which these effects are due are (among others): (1) power factor, (2) inductance, (3) permittance or capacitance, and (4) skin effect.* Where the circuits are not of great length it is not necessary to consider these effects. But, where the circuits are long they may be of considerable consequence. Permittance need seldom be considered except with rather-high-voltage circuits. Hence, these permittance effects are not treated. The method for designing—that is, for computing the wire sizes for alternating-current circuits of different characteristics—will be outlined in following articles.

177. Power Factors of the Apparatus or Equipment which the circuit serves must often be known before the circuit can be effectively designed. If the exact power factor is not known or cannot be obtained from the manufacturer of the apparatus in question, approximate values† can be used. The power factor of the load, if it be other than 100 per cent., may affect the voltage drop in the line considerably. This fact is brought out in a number of the examples which follow.

NOTE.—For ordinary wiring calculations where more definite data are lacking it can be assumed that the power factor of loads will be about as follows: Incandescent lighting only, from 100 per cent. down to 95 per cent.; incandescent lighting and motors, 85 per cent.; motors only, 80 per cent.

178. The Effect of Line Reactance must also be given consideration. Practically all alternating-current circuits have

* These phenomena are discussed and explained in more detail in the author's PRACTICAL ELECTRICITY.

† See the author's AMERICAN ELECTRICIANS' HANDBOOK for a comprehensive list of operating power factor of different kinds of apparatus.

some reactance due to electromagnetic inductance* (see Tables 190*A* and 190*B* for reactance-drop values). The effect of line reactance is to cause a drop in voltage somewhat similar to that caused by resistance. Where all of the wires of a circuit, two wires for a single-phase and three wires for a three-phase circuit, are carried in the same conduit or where the wires are separated less than an inch between centers, the effect of inductive reactance can ordinarily be neglected. Where the circuit conductors are larger than say No. 2 wire and separated from one another by more than a few inches, the effect of inductive reactance in the line circuit may increase the voltage drop considerably over that drop which is due to resistance alone. In designing circuits, every circuit which is long or the conductors of which are of large cross-sections or widely separated should be investigated for line reactance drop by utilizing the methods outlined in Art. 190.

179. The Line Reactance of Aerial Circuits on Pole Lines where the wires are widely separated, is apt to be relatively large. Line reactance increases as the size of the wire increases and as the distance between wires increases. These statements may be verified by referring to the values in Tables 190*A* and 190*B*.

180. Line or Circuit Reactance May Be Reduced in Two Ways.—One of these is to diminish the distance between wires. The extent to which the reactance may be diminished by this method is limited, in the case of the pole line, to the least separation permissible between conductors, due consideration being given to the separation required for insulation and to the separation necessary to prevent the wires from swinging together in the middle of a span. In inside wiring knob-and-cleat work, the minimum separation between conductors is limited to the minimum spacing specified by the *National Electrical Code.*† Where the conductors are in conduit they then lie so close together that the factor of inductive reactance with them is ordinarily negligible.

The other way of reducing line reactance is to divide the

* See the author's PRACTICAL ELECTRICITY for a discussion of electromagnetic inductance and reactance.

† See the author's WIRING FOR LIGHT AND POWER.

copper into a greater number of circuits and to arrange these circuits so that there is no inductive interaction. Thus, in Fig. 101 the circuit of *II* will have less inductive reactance than the circuit of *I*, although it has the same total circular mils area, because it is subdivided. How and why subdivision

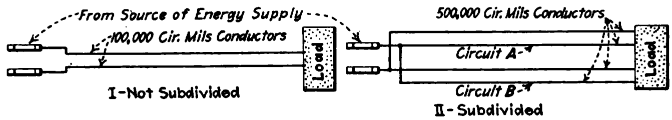


FIG. 101.—Showing how a conductor may be subdivided.

decreases the reactance of a circuit will be evident from a consideration of some of the numerical examples which follow.

NOTE.—Voltage drop in lines, due to inductive reactance, is best diminished* by subdividing the copper or by bringing the conductors close together. It is little affected by changing the size of the conductor.

181. The Arrangement of Conductors in Polyphase Circuits† will next be given consideration. The directions for the calculation of polyphase circuit conductors which are given in following articles, hold only with certain arrangements of the circuit conductors. These arrangements are, however, the ones which ordinarily are, or which may be readily adopted. These conditions need not be considered where the circuit in question is short and, in general, they need not be considered in interior wiring circuits. They become of importance, however, with circuits extending possibly for a distance of over a mile.

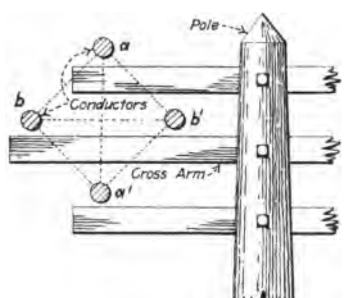


FIG. 102.—Arrangement of two-phase conductors on cross arms.

182. The Two Circuits of a Two-phase Transmission Should Be so Arranged That There Is No Inductive Interaction.†—

* Ralph Mershon.

† Westinghouse Electric & Manufacturing Company publication.

Such an arrangement may be effected by either of the two methods shown respectively in Figs. 102 and 103. Fig. 102 shows the two wires, *a* and *a*, of one circuit and the other two, *b* and *b*, of the other circuit at the opposite ends of the

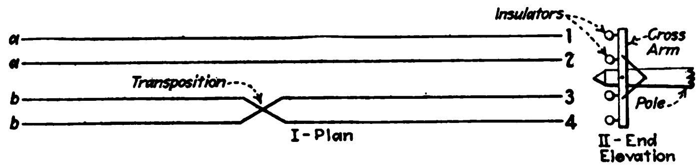


FIG. 103.—Arrangement of two-phase conductors on crossarm.

diagonals of a square. With such an arrangement there is no inductive interaction between the two circuits since none of the flux lines due to one of the circuits can cut the other. Fig. 103 shows the two circuits side by side (they may be in any other relative position, provided it is preserved throughout) and the wires of the circuit, *b* and *b*, interchanged or transposed at their middle point. Such an arrangement fulfills the requirements since all of the linkages from *a* and *a* to *b* and *b* and from *b* and *b* to *a* and *a* in one-half of the transmission are exactly offset by the same number of opposite linkages in the other half of the transmission.

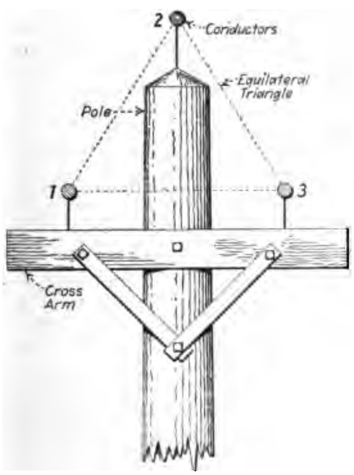


FIG. 104.—Symmetrical arrangement of conductors, three-phase circuit.

183. The Arrangement of the Three Wires of a Three-phase Transmission should be such that they are symmetrically related. Figs. 104 and 105 show two methods of effecting this arrangement. In Fig. 104 each of the three wires is at a corner of an equilateral triangle. In Fig. 105 all three of the wires are on the same crossarm and they are twice transposed.

One transposition, *A*, is at one-third of the transmission distance and the other, *B*, at two-thirds of the transmission distance. In Fig. 104, since each of the wires carries the same current and because of the symmetrical arrangement of the conductors, the inductive interaction between any one wire and the remaining two is the same regardless of which wire is considered. With the arrangement of Fig. 105 the same condition holds and can be verified by tracing the positions of the wires throughout their lengths.

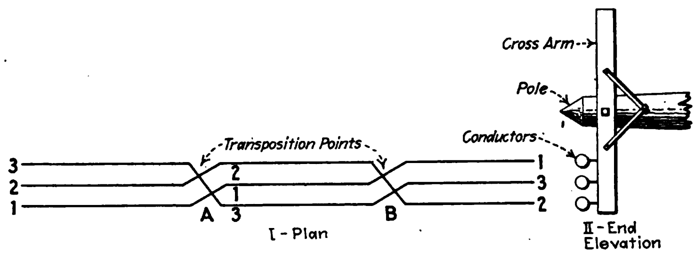


FIG. 105.—Arrangement of conductors on crossarm.

NOTE.—The arrangement of Fig. 105 may be used where all of the power is transmitted to the end of the line. Where all of the power is transmitted to the end of the line, only two transpositions, *A* and *B*, as shown, are necessary. But if power is tapped off at intermediate points and perfect neutralization of inductive interaction is desired the wires should be interchanged as shown in Fig. 105 between locations at which "tap offs" to the line are made. That is, there should be two transpositions between the generating station and the first tap off; two between the first and second tap off, etc.

184. Where the Triangular Arrangement of Three-phase Conductors Is Employed the Wires May Be Interchanged or Transposed.—This is unnecessary, however, unless it is impossible to arrange the wires in a triangle which is practically equilateral or unless there are two or more circuits running parallel to one another and it is desired to have them inductively independent. Where it is desired that the parallel circuits be inductively independent they can be disposed as suggested in Fig. 106. This illustration shows a top view of the triangular arrangement. The first circuit, *I*, runs straight

through. The second, *II*, is interchanged twice. The third, *III*, is interchanged eight times and the fourth would be interchanged 26 times, etc. If it is necessary to interchange the first circuit because of any inequality in the sides of the triangle, *II* must be taken as the first circuit, *III* as the second, etc. Also *II* and *III* of Fig. 106 may be followed in transposing three-phase circuits, the three wires of which are on the same crossarm, as in Fig. 105. Then *II* is the first circuit and *III* is the second circuit and so on.

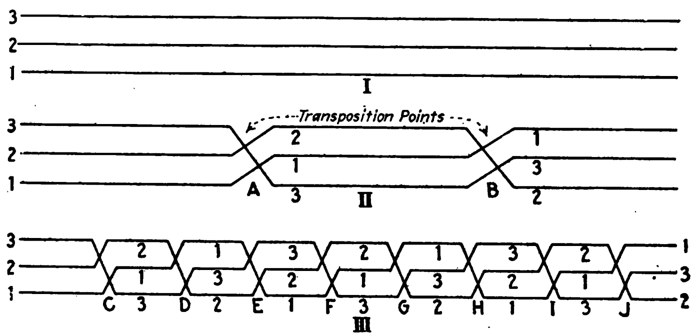


FIG. 106.—Transposition of three-phase circuits.

185. If an Electrically Symmetrical Arrangement Is Not Employed (that is, unless one of the arrangements of conductors described in the articles just preceding is not utilized) the unbalanced inductive reactance which will result will cause an unbalancing of the system. Such an unbalancing will be of little consequence in a short system but in a long transmission it may cause considerable annoyance. For example, if the four wires of a two-phase transmission or the three wires of a three-phase transmission are strung straight through on the same crossarm without transposition unbalancing of the system will result.

NOTE.—The rule given in Art. 198 for calculating a three-phase line applies closely but not exactly to Fig. 105, for the reason that the arrangement of Fig. 105 cannot be exactly replaced by two single-phase circuits the wires of which are the same distance apart as the adjacent wires of Fig. 105. No two wires in Fig. 105 are the same distance apart

throughout their length. They are at one distance apart for two-thirds of the length and twice that distance for the remaining one-third. The equivalent single-phase circuit must, therefore, have between wires a distance intermediate between that of adjacent and extreme wires in Fig. 105.

EXAMPLE.—Consider a three-phase line of which the adjacent wires are 18 in. apart. The equivalent single-phase circuits must have their wires apart a distance intermediate between 18 in. and 36 in. What this distance is can be determined by referring to a table of reactances. Consider a No. 0 wire and a frequency of 60 cycles. In Table 190*A* the constant for an 18-in. separation is 0.228. That for 36 in. is 0.259. Therefore, the constant of the equivalent single-phase circuit is: $(0.228 + 0.228 + 0.259) \div 3 = 0.238$, which corresponds to a spacing distance of about 22 in. This shows one advantage which the triangular arrangement has over that of Fig. 105, because for the same distance between adjacent conductors, the reactances with the triangular arrangement (Fig. 104) is less than with that of Fig. 105. If an accurate solution is necessary, with an arrangement like that of Fig. 105, the average constant for any two wires must be taken in calculating the reactance volts.

186. In Calculating Wire Sizes for Single-phase Alternating-current Incandescent-lighting Interior Circuits formula (54) is ordinarily used. That is, *cir. mils* $= (22 \times I \times L) \div V$ may be applied in precisely the same way as if the circuit were a direct-current circuit. The result which this formula will give is strictly accurate (assuming 11 ohms is the resistance of a circular mil-foot of copper) where the load is non-inductive. That is, where its power factor is 100 per cent. and where the line or circuit to the load has no reactance. The results obtained by using formula are not theoretically accurate for actual alternating-current circuits, because the effects of the power factor of the lamp load and of the line reactance are not considered.

NOTE.—Experience has shown that the results obtained by using formula (54) are sufficiently accurate for practical circuit design for wiring small and medium-sized residences, stores, factories and the like, for incandescent lighting. Where the conductors are carried in conduit, the results will be quite accurate for any size wire used in practice. Formula (54) can always be used with safety for computing branch circuits for interior incandescent lighting or where main or feeder circuits, composed of conductors of, say, larger than No. 2 wire and separated from one another more than a few inches, are being designed. The wire size indicated by the above formula should be checked by the theoretically

accurate method outlined in a following paragraph. From this it can be ascertained whether the voltage drop in the particular case under consideration will be excessive.

EXAMPLE.—Any of the examples given in the preceding articles for direct-current, two-wire or three-wire circuits (for incandescent lamps only, not for motors) may be taken as examples of single-phase alternating-current circuits if it be assumed that the lines have no reactance. As noted, this is a safe assumption for ordinary low-voltage open-wire or conduit interior incandescent lighting circuits.

187. The Method of Computing the Wire Size for a Single-phase Alternating-current Circuit Where the Line Has No Reactance or may be assumed to have no reactance, will now be considered. For an approximate solution formula (54) may be used. This will always give a result which is on the safe side provided the line has practically no reactance. However, in applying formula (54) for alternating-current circuits, the value of I, in amperes, must be the actual current which flows in the alternating-current line. That is, it is the current stamped on the nameplate of the machine or device served, or this value for I may be obtained by dividing the actual watts taken by the voltage times the power factor or: $I = (watts) \div (voltage \times power\ factor)$.

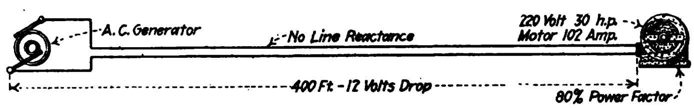


FIG. 107.—Wire size for A.C. circuit (no line reactance).

EXAMPLE.—What size wire should be used for the open-wire motor circuit of Fig. 107? The circuit is 400 ft. long and serves a 30-h.p., alternating-current motor which, as rated on the nameplate, is taking 102 amp. Since the circuit wires are very close together there is practically no line reactance. The allowable drop is 12 volts. SOLUTION.—Current = 102; distance = 400 ft.; drop = 12 volts. Substitute in formula (54):

$$cir.\ mils = \frac{22 \times I \times L}{V} = \frac{22 \times 102 \times 400}{12} = 74{,}800\ cir.\ mils$$

Referring to Table 154, the next larger wire size is No. 1 which has an area of 83,690 cir. mils and safely carries, for exposed wire (slow-burning or weather-proof insulation) 150 amp.

Since to conform to *National Electric Code* rules a motor branch circuit must be capable of carrying at least 25 per cent. over-current the wires to this motor (Fig. 107) must be capable of safely carrying 102: × 1.25 = 127.5 *amp*. The No. 1 wire will do this. It should be understood that the result, 74,800 cir. mils, obtained above is not exactly accurate. With 102 amp. flowing and the load at 80 per cent. power factor the volts loss in the line (assuming no line reactance) will be something less than 12 volts, as explained in the following article.

188. The Actual Volts Loss in a Single-phase Alternating-current Line Where It Has No Reactance Can Be Determined by Drawing a Vector Diagram to scale, as explained in the following example. This method can be used for the solution of any problem in which the line reactance can be neglected.

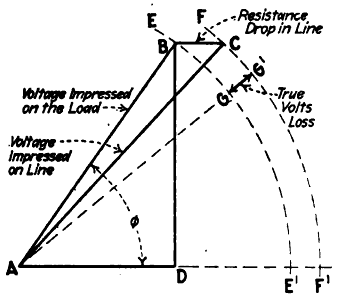


FIG. 108.—Voltage diagram of circuit with no line reactance.

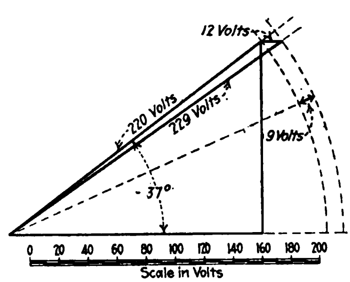


FIG. 109.—Solution of problem of Fig. 107.

DIRECTIONS.—See Fig. 108. Find the power factor of the load or use an assumed power factor. Refer to a table of cosines* and find the lag angle to which this power factor corresponds. Lay out the angle ϕ equal to the lag angle. Measure off distance AB proportional to the voltage impressed on a load. Lay off BC, parallel to AD, proportional to the resistance drop in the line. Then AC will be proportional in length to the voltage impressed on the line. The difference in length between AB and BC will then be proportional to the actual volts loss in the line. This difference is obtained by striking the arcs EE^1 and FF^1 and measuring the distance between them, as for example, GG^1.

EXAMPLE.—Fig. 109 shows the problem of Fig. 107 solved graphically from which it is apparent that the true volts loss in the line would be 9 volts, whereas the formula (54), as shown in preceding Art. 183, indicates that the loss would be 12 volts. Actually, 12 volts is the resistance drop

* See the author's AMERICAN ELECTRICIANS' HANDBOOK.

in the line. It may seem odd that the total volts drop in the line is less than the resistance drop. This condition is due to certain properties of alternating currents and frequently occurs. Instead of drawing a diagram like that of Fig. 109, the problem can also be solved by using the Mershon diagram, as described in following Art. 190*A*.

189. Where It Is Necessary to Find the Resistance Drop With a Given Conductor formula (51) may be utilized as indicated in the following example.

EXAMPLE.—What is the resistance drop in a circuit 400 ft. long of No. 1 wire when it is carrying 102 amp.? SOLUTION.—First from Table 190*A* it is found that the area, in circular mils, of a No. 1 wire is 83,690. Now substituting the values in formula (51):

$V = IR$

$$V = \frac{22 \times I \times L}{cir.\ mils} = \frac{22 \times 102 \times 400}{83{,}690} = \frac{997{,}600}{83{,}690} = 11.9\ volts.$$

$R = \rho \frac{A}{L}$

190. The Graphic Method of Computing the Wire Size for a Single-phase Alternating-current Circuit Where the Line Has Reactance will now be explained. There is no direct method of solving such problems. One serviceable method is that (which will be explained) of assuming a certain conductor on the basis of energy (not voltage) loss and then checking it graphically (or with the Mershon diagram of Fig. 115) to ascertain whether or not the voltage loss in it is excessive. If the voltage loss is excessive, a conductor of another size must be tried or the circuit must be subdivided, as suggested in a preceding article, until an arrangement of conductors is found which will maintain the drop within the specified limit. The graphic method is best explained by the solution of specific examples. Figs. 110 and 111 show typical voltage vector diagrams for circuits, the component vectors being labeled on the diagrams.

EXAMPLE.—What size wire should be used for the single-phase circuit of Fig. 112? The load consists of twelve hundred 50-watt incandescent lamps (60,000 watts total); the power factor is 98 per cent.; the feeder is 525 ft. long and the voltage at its end is to be 120 volts; the conductors are supported on a pole line 8 in. apart; allowable energy loss is 10 per cent. of the energy transmitted and the voltage drop in the line must not exceed 10 or 12 per cent. (This is a much greater voltage drop than is ordinarily allowable. It is used in this problem to exaggerate the values

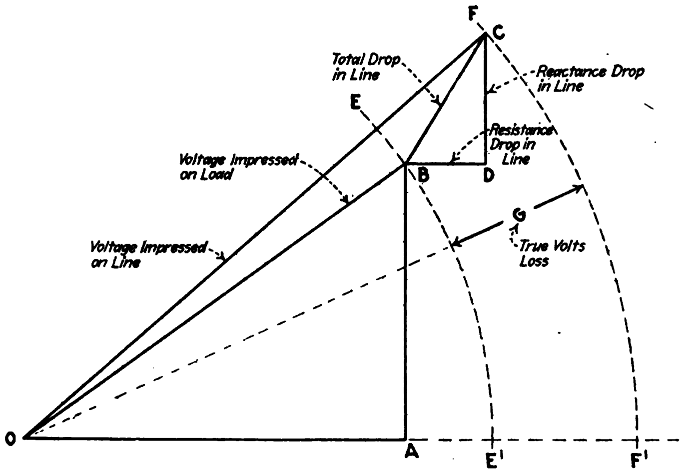


FIG. 110.—Voltage diagram of circuit with line reactance, load at less than 100 per cent. power factor.

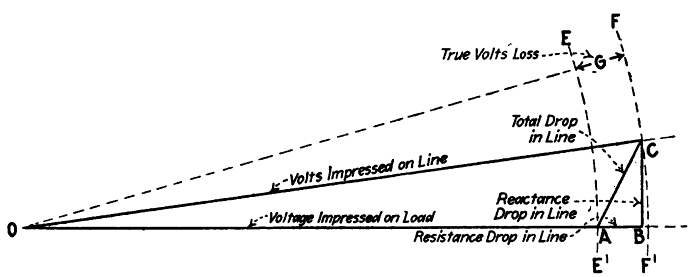


FIG. 111.—Voltage diagram of circuit with line reactance and load at 100 per cent. power factor.

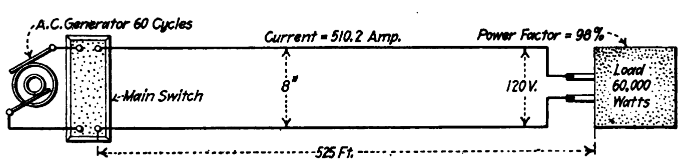


FIG. 112.—Find size wire for circuit.

involved and thus bring out the facts.) SOLUTION.—First find the current which will flow in the line, thus:

$$I = \frac{P}{V \times p.f.} = \frac{60{,}000}{120 \times 0.98} = 510.2\ amp.$$

The allowable energy loss is 10 per cent. or $0.10 \times 60{,}000\ watts = 6{,}000\ watts$. The size conductor that will give a loss of 6,000 watts may be determined from formula (60) thus:

$$cir.\ mils = \frac{22 \times I^2 \times L}{P} = \frac{22 \times 510.2 \times 510.2 \times 525}{6{,}000} = 510{,}000\ cir.\ mils.$$

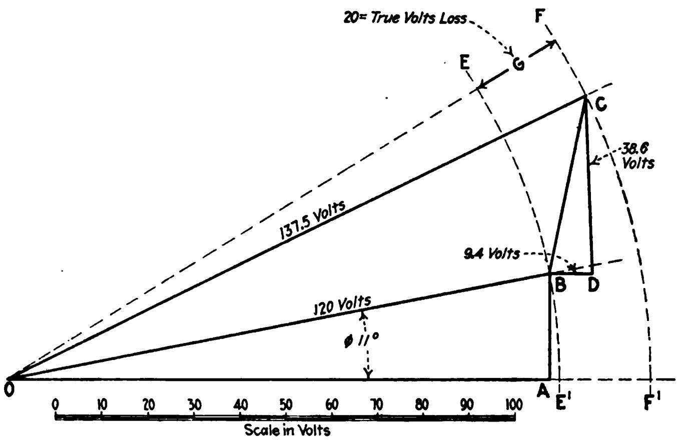


FIG. 113.—Solution with 600,000-cir. mil conductor.

That is, a 510,000-cir. mil conductor would maintain the energy loss within 10 per cent. Consider the vector diagram of Fig. 113. Find the lag angle ϕ corresponding to a power factor of 98 per cent. This, from a table of cosines, is found to be 11 deg. Lay out angle ϕ equal to 11 deg., as indicated in Fig. 113. Now, lay off OB proportional in length to the pressure to be impressed on the load, 120 volts.

Lay off BD, parallel to OA, proportional to the resistance drop in the line. This resistance drop equals the line resistance times the line current. From Table 190A, it is found that the resistance of 1,000 ft. of 600,000 cir. mil circuit (2,000 ft. of line) is 0.035 ohm. Then the resistance drop is calculated thus:

$$I \times R = \frac{510.2 \times 0.035\ \text{ohm} \times 525\ ft.}{1{,}000} = 9.4\ volts.$$

That is, the resistance drop in the line of Fig. 112 is 9.4 volts. In the diagram of Fig. 113 BD is then laid off proportional to 9.4 volts.

Now lay off DC at right angles to BD proportional to the reactance drop of the line. The reactance drop equals (*the line reactance*) × (*the line current*). From Table 190*A* it is found that the reactance drop of 1,000 ft. of 600,000-cir. mil circuit (2,000 ft. of conductor) is, for a frequency of 60 cycles and a wire separation of 8 in., 0.144 ohm. The reactance drop is now calculated thus:

$$I \times X = (510.2) \times \frac{(0.144\ ohm \times 525\ ft.)}{1{,}000} = 38.6\ volts.$$

A line, OC (Fig. 113), is then drawn and it will be proportional to the pressure, 137.5 volts in this case, which must be impressed on the end of the line nearest the generator (Fig. 112) to maintain the voltage at the load at 120 volts.

The true volts line loss is proportional to the difference between the lengths OB and OC. It is obtained by striking the arcs EE^1 and FF^1 and measuring the distance G between them. In this example the true

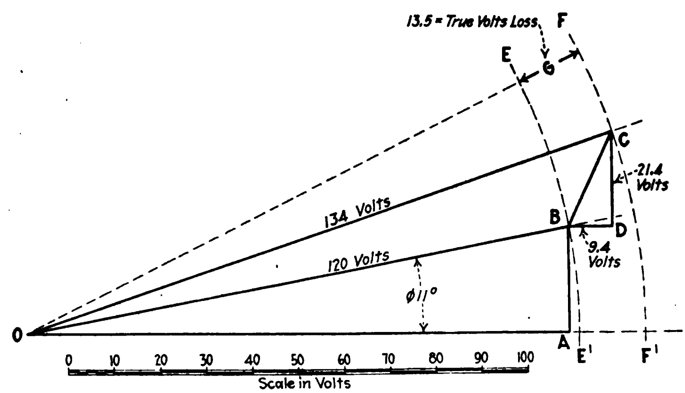


FIG. 114.—Solution with 300,000-cir. mil conductors.

line loss is 20 volts. The percentage volts drop is 20 ÷ 120 = 16.6 per cent., which is too high to satisfy the requirements of this example, wherein it is specified that "the allowable voltage drop in the line must not exceed 10 or 12 per cent." Hence, another conductor arrangement must be tried.

The volts line drop in this case is due mainly to reactance (Fig. 113) and can, therefore, be decreased by decreasing the reactance. The reactance could be made smaller by bringing the wires closer together but the example (Fig. 112) specifies that conductors are to be 8 in. apart. The other method of decreasing the reactance drop is to subdivide the circuit. This will now be tried. Two circuits of 300,000 cir. mils conductors in parallel will be considered instead of one 600,000-cir.-mil cir-

190A. [1]60 Cycles.—Table for Finding Drop in A.-C. Lines with the Mershon Diagram of Fig. 115.—[1]60 Cycles

Size of wire (cir. mils) and B. & S. gage	Safe carrying capacity, N.E.C.		Resistance-volts in 1,000 ft. of line (2,000 ft. of wire) for 1 amp. (The values in this column are really the resistances of 2,000 ft. of conductor at 75 deg. F.	Reactance-volts in 1,000 ft. of line (2,000 ft. of wire) for 1 amp. at 7,200 alternations per minute (60 cycles per second) for the distance given in inches between centers of conductors. (The values in these columns are really the reactances of 2,000 ft. of conductor)															
	Rubber ins.	Other ins.		½	1	2	3	4	5	6	8	9	12	18	24	30	36	48	96
14– 4,107	15	20	5.06	.138	.178	.218	.220	.233	.244	.252	....	.271	.284	.302	....	....	....	....	....
12– 6,530	20	25	3.18	.127	.159	.190	.210	.223	.233	.241	....	.260	.273	.292	....	....	....	....	....
10– 10,380	25	30	2.00	.116	.148	.180	.199	.212	.223	.221	.244	.249	.262	.281	....	....	....	.326	.358
8– 16,510	35	50	1.26	.106	.138	.169	.188	.201	.212	.220	.233	.238	.252	.270	.284	.293	.302	.315	.347
6– 26,250	50	70	0.790	.095	.127	.158	.178	.190	.210	.209	.222	.228	.241	.260	.272	.283	.291	.305	.337
4– 41,740	70	90	0.498	.085	.117	.149	.176	.180	.190	.199	.211	.217	.230	.249	.262	.272	.281	.294	.326
2– 66,370	90	125	0.312	.074	.106	.138	.156	.169	.180	.188	.194	.206	.220	.238	.252	.262	.270	.277	.309
1– 83,690	100	150	0.248	.068	.101	.132	.151	.164	.174	.183	.190	.201	.214	.233	.246	.256	.265	.273	.305
0–105,500	125	200	0.196	.063	.095	.127	.145	.159	.169	.177	.184	.196	.209	.228	.241	.251	.259	.267	.299
2/0–133,100	150	225	0.156	.057	.090	.121	.140	.153	.164	.172	.179	.190	.204	.222	.236	.246	.254	.262	.294
3/0–167,800	175	275	0.122	.052	.085	.116	.135	.148	.158	.167	.173	.185	.199	.217	.230	.241	.249	.255	.287
4/0–211,600	225	325	0.098	.046	.079	.111	.130	.143	.153	.161	.168	.180	.193	.212	.225	.235	.244	.251	.283
250,000	235	250	0.085	....	.075	.106	.125	.139	.148	.157	.164	.175	.189	.207	.220	....	....	....	....
300,000	275	400	0.075	....	.071	.103	.120	.134	.144	.153	.160	.171	.185	.203	.217	....	....	.242	.274
350,000	300	450	0.061	....	.067	.099	.118	.128	.141	.149	.157	.168	.182	.200	.213	....	....	....	....
400,000	325	500	0.052	....	.064	.096	.114	.127	.138	.146	.154	.165	.178	.197	.209	....	....	.237	.269
500,000	400	600	0.042	....	....	.090	.109	.122	.133	.141	.148	.160	.172	.192	.202	....	....	.231	.263
600,000	450	680	0.035	....	....	.087	.106	.118	.128	.137	.144	.155	.169	.187	.200	....	....	.226	.258
700,000	500	760	0.030	....	....	.083	.102	.114	.125	.133	.141	.152	.165	.184	.197	....	....	.223	.255
800,000	550	840	0.026	....	....	.080	.099	.112	.122	.130	.138	.148	.162	.181	.194	....	....	.220	.252
900,000	600	920	0.024	....	....	.077	.096	.109	.119	.127	.135	.146	.159	.178	.191	....	....	.218	.250
1,000,000	650	1,000	0.022	....	....	.075	.094	.106	.117	.125	.132	.144	.158	.176	.188	....	....	.215	.247

[1] For other frequencies the reactance will be in direct proportion to the frequency.

How to Use the Mershon Diagram.—By means of the above table calculate the resistance-volts and reactance-volts in the line, and find what per cent. each is of the e.m.f. delivered at the end of the line. Starting from the point on the chart (Fig. 115) where the vertical line corresponding with power factor of the load intersects the smallest circle, lay off in per cent. the resistance e.m.f. horizontally and to the right; from the point thus obtained lay off upward in per cent. the reactance e.m.f. The circle on which the last point falls gives the drop in per cent. of the e.m.f. delivered at the end of the line. Every tenth circle arc is marked with the per cent. drop to which it corresponds. See accompanying examples.

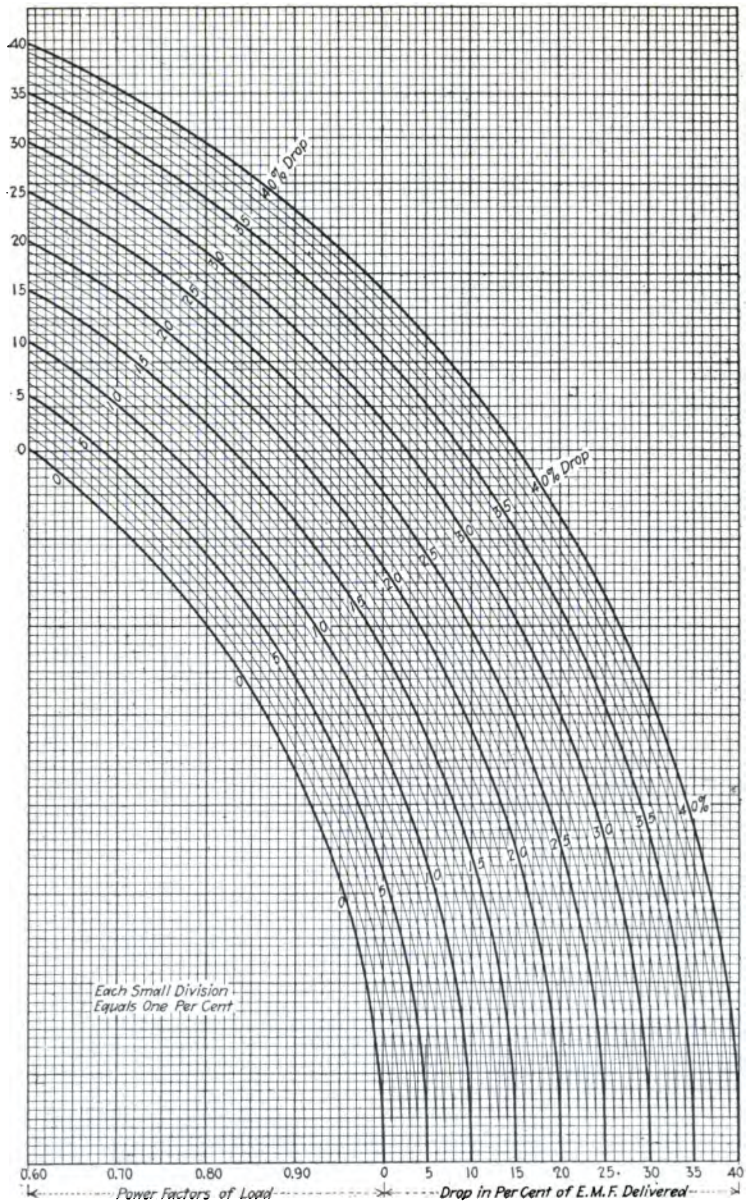


FIG. 115.—The Mershon diagram. See Arts. 190A and 190B for directions as to its use and application.

190B. [1]25 Cycles—Table for Finding Drop in A.-C. Lines with the Mershon Diagram of Fig. 115—[1]25 Cycles

Size of wire (cir. mils) and B. & S. gage	Safe carrying capacity, N.E.C.		Resistance-volts in 1,000 ft. of line (2,000 ft. of wire) for 1 amp. (The values in this column are really the resistances of 2,000 ft. of conductor at 75 deg. F.	Reactance-volts in 1,000 ft. of line (2,000 ft. of wire) for 1 amp. at 3,000 alternations per minute (25 cycles per second) for the distance given in inches between centers of conductors. (The values in these columns are really the reactances of 2,000 ft. of conductor)										
	Rubber, ins.	Other, ins.		½	1	2	3	4	5	6	9	12	18	24
14– 4,107	15	20	5.06	0.057	0.071	0.084	0.093	0.097	0.102	0.105	0.113	0.118	0.126	
12– 6,530	20	25	3.18	0.053	0.066	0.080	0.087	0.094	0.097	0.101	0.108	0.113	0.122	
10– 10,380	25	30	2.00	0.049	0.062	0.075	0.083	0.088	0.092	0.096	0.104	0.110	0.117	
8– 16,510	35	50	1.26	0.044	0.057	0.071	0.078	0.084	0.088	0.092	0.099	0.105	0.113	
6– 26,250	50	70	0.790	0.040	0.053	0.066	0.074	0.079	0.084	0.087	0.095	0.100	0.108	
4– 41,740	70	90	0.498	0.035	0.049	0.062	0.070	0.075	0.079	0.083	0.091	0.096	0.104	
2– 66,370	90	125	0.312	0.031	0.044	0.057	0.065	0.071	0.075	0.078	0.086	0.092	0.099	
1– 83,690	100	150	0.248	0.028	0.042	0.055	0.063	0.068	0.073	0.076	0.083	0.089	0.097	
0–105,500	125	200	0.196	0.026	0.040	0.053	0.061	0.066	0.070	0.073	0.082	0.087	0.095	
2/0–133,100	150	225	0.156	0.024	0.037	0.051	0.058	0.064	0.068	0.072	0.079	0.085	0.093	
3/0–167,800	175	275	0.122	0.022	0.035	0.048	0.056	0.062	0.066	0.070	0.077	0.083	0.091	
4/0–211,600	225	325	0.098	0.091	0.033	0.046	0.053	0.059	0.064	0.067	0.075	0.081	0.088	
250,000	235	250	0.085	.....	0.031	0.044	0.051	0.058	0.062	0.065	0.073	0.079	0.086	0.092
300,000	275	400	0.075	.....	0.030	0.043	0.050	0.056	0.060	0.064	0.071	0.077	0.084	0.090
350,000	300	450	0.061	.....	0.028	0.041	0.049	0.054	0.059	0.062	0.070	0.076	0.083	0.089
400,000	325	500	0.052	.....	0.027	0.040	0.048	0.053	0.057	0.061	0.069	0.075	0.082	0.087
500,000	400	600	0.042	.....	.....	0.038	0.046	0.051	0.055	0.059	0.067	0.072	0.080	0.085
600,000	450	680	0.035	.....	.....	0.036	0.044	0.049	0.053	0.057	0.065	0.070	0.078	0.083
700,000	500	760	0.030	.....	.....	0.035	0.042	0.048	0.052	0.056	0.063	0.069	0.077	0.082
800,000	550	840	0.026	.....	.....	0.033	0.041	0.047	0.050	0.054	0.062	0.068	0.075	0.081
900,000	600	920	0.024	.....	.....	0.032	0.040	0.046	0.050	0.053	0.061	0.066	0.074	0.080
1,000,000	650	1,000	0.022	.....	.....	0.031	0.039	0.044	0.049	0.052	0.060	0.065	0.073	0.079

[1] For other frequencies the reactance will be in direct proportion to the frequency.

How to Use the Mershon Diagram.—By means of the above table calculate the resistance-volts and the reactance-volts in the line, and find what per cent. each is of the e.m.f. delivered at the end of the line. Starting from the point on the chart (Fig. 115) where the vertical line corresponding with power factor of the load intersects the smallest circle, lay off in per cent. the resistance e.m.f. horizontally and to the right; from the point thus obtained lay off upward in per cent. the reactance e.m.f. The circle on which the last point falls gives the drop in per cent. of the e.m.f. delivered at the end of the line. Every tenth circle arc is marked with the per cent. drop to which it corresponds. See accompanying examples.

cuit. With the two 300,000-cir. mil circuits, the resistance drop will remain the same as before, because, although each conductor is one-half the size it was formerly, it carries but one-half the current that it did formerly.

Lay out a diagram like that of Fig. 114. The angle ϕ will again be 11 deg. and the lines OB and BD, representing, respectively, the voltage impressed on the load and the resistance drop in the line, will be proportional to 120 and to 9.4 volts as before.

To lay out CD, which is proportional in length to the reactance drop in the line, refer to Table 190A and note that the reactance of 2,000 ft. of 300,000 cir. mil conductor (1,000 ft. of circuit) is, for an 8-in. separation and a frequency of 60 cycles, 0.160 ohm. Then the reactance drop will be (the current is now one-half of the former current or 510.2 ÷ 2 = 255.1 amp.):

$$I \times X = (255.1\ amp.) \times \frac{0.160 \times 525}{1{,}000} = 21.4\ volts.$$

DC (Fig. 114) is, then, laid off proportional in length to 21.4 volts. The line OC is now drawn and it is found that it scales 134 volts. The true volts drop in the line, G, is found to measure 13.5 volts. The percentage drop is, therefore, now 13.5 ÷ 120 = 11.3 *per cent.* Hence, the arrangement obtained by subdividing the circuit into two 300,000-cir. mil circuits in parallel meets the requirements of the example.

191. The Determination With a Mershon Diagram of the Wire Size for a Single-phase Alternating-current Circuit Where the Line Has Reactance will now be considered. The problem solved in preceding Art. 190 and similar ones can be handled more rapidly and with less effort by using the Mershon diagram (Fig. 115) than by following the graphic method just outlined in Art. 190. However, it is desirable that one be familiar with the graphical method of Figs. 112 and 113, because it can be utilized when the Mershon diagram graph (Fig. 115) is not available. Furthermore, if one understands the method of Figs. 112 and 113 he will more readily comprehend the application of the Mershon diagram.

NOTE.—In using the Mershon diagram, the general procedure is practically the same as with the graphical method. The conductor size is first tentatively computed by applying a formula so that the energy loss will be a certain percentage of the energy transmitted. The tentative conductor size thus obtained is checked with a Mershon diagram to ascertain whether or not the true volts line drop which will occur with it will be excessive. If the line drop with a conductor of this size is exces-

sive then a different size conductor or a different arrangement of conductors must be used.

EXAMPLE.—What size wire should be used for the feeder circuit of Fig. 116? The load consists of 24 kw. (24,000 watts) of mercury vapor lamps. The circuit is 100 ft. long. The pressure at the receiver end should be 240 volts. The wires are carried in conduit. The power factor of the mercury vapor lamp load is 98 per cent. The frequency is 60 cycles. The energy loss should not exceed 2 per cent. The true volt line drop should not exceed 2 per cent. of the receiver voltage. SOLUTION.—The allowable energy loss = 0.02 = 24,000 × 480 *watts.* Allowable volts drop = 0.02 × 240 = 4.8 *volts.*

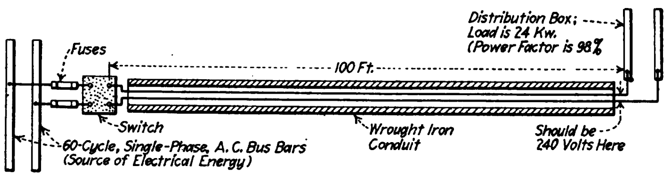


FIG. 116.—Determination of size of wire for an alternating-current circuit in conduit.

$$\textit{Line current} = I = \frac{P}{E \times p.f.} = \frac{24{,}000}{240 \times 0.98} = \frac{100}{0.98} = 102\ \textit{amp.}$$

To compute the size conductor that will give a 480-watt energy loss formula (60) is used, thus:

$$\textit{cir. mils} = \frac{I^2 \times 22 \times L}{P} = \frac{102 \times 102 \times 22 \times 100}{480} = 47{,}700\ \textit{cir. mils.}$$

Now a 47,700-cir. mil conductor (Table 190*A*) most nearly corresponds to a No. 3 wire which has an actual area of 52,630 cir. mils and, with rubber insulation (which must be used in conduit wiring) will safely carry 76 amp. However, the load in this problem is 102 amp., so No. 3 can not be used. No. 1 wire, which (Table 190*A*) safely carries 100 amp. and which would be safe for the 102 amp. of this problem, will be checked for true volts drop by using the Mershon diagram: To use the diagram it is first necessary to find the resistance drop and the reactance drop. From Table 190*A*, the resistance of 1,000 ft. of No. 1 two-wire circuit (2,000 ft. of wire) is 0.248 ohms. Then the resistance drop, which equals current multiplied by resistance, of the 100 ft. of circuit of this problem is:

$$I \times R = (102) \times \frac{0.248 \times 100}{1{,}000} = 2.5\ \textit{volts.}$$

Then the percentage voltage drop is: 2.5 ÷ 240 = 1.04 per cent. Also from Table 190*A*, the reactance of 1,000 ft. of No. 1 wire circuit for 60 cycles and a ½-in. separation between conductors (No. 1 conductors

in conduit are about ½ in. between centers) is 0.028 ohm. Then the reactance drop, which equals *current times reactance* is, for 100 circuit ft.:

$$I \times X = (102) \times \frac{0.028 \times 100}{1,000} = 0.286 \textit{ volts}.$$

The percentage drop is: 0.286 ÷ 240 = 0.00119 = 0.12 *per cent.* Now refer to the Mershon diagram of Fig. 115 and lay off the percentage resistance and reactance drops above found as suggested in Fig. 117.

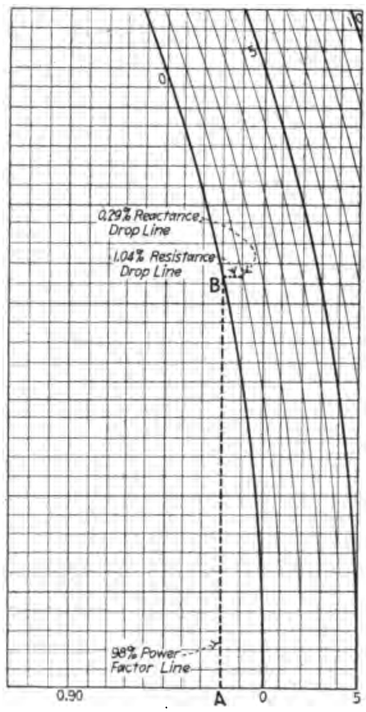


FIG. 117.—Showing the application of the Mershon diagram to the problem of Art. 191.

Find the vertical line in the diagram corresponding to the power factor—98 per cent. in this example—of the load and follow it, AB, upward until it intersects the smallest circle marked O. From this point of intersection lay off to the right horizontally the percentage resistance drop, that is, 1.04 (about 1 horizontal division in length) and from this last point lay off vertically upward the percentage reactance drop, 0.29 (about $\frac{3}{10}$ of 1 vertical division). This last point lies just inside of the 1 per cent. circle so the true volts loss with a No. 1 wire would be about 1 per cent. That is, the drop would be 0.01 × 240 *volts* = 2.4 *volts.*

The voltage impressed on the end of the circuit nearest the generator would have to be: $240 + 2.4 = 242.4$ *volts*. The true line drop, 2.4 volts, is well within the 4.8-volt limit specified in the example and the energy loss will be less than 2 per cent. because it was necessary to use No. 1 wire to carry the current.

EXAMPLE.—What size rubber-insulation wire should be used for the circuit (Fig. 118) to the 50-h.p., 60-cycle, single-phase induction motor there illustrated? The efficiency of the motor is 90 per cent. Its power factor is 85 per cent. The conductors are to be exposed and 4 in. apart. A 4 per cent. energy loss is allowable and the true volts line drop must not exceed 6 or 7 per cent. SOLUTION.—First find the load in apparent watts:

$$Apparent\ watts = \frac{h.p. \times 746}{E \times p.f.} \frac{50 \times 746}{0.9 \times 0.85} = 48{,}758\ apparent\ watts.$$

$$Line\ current = \frac{apparent\ watts}{E} = \frac{48.758}{240} = 200\ amp.$$

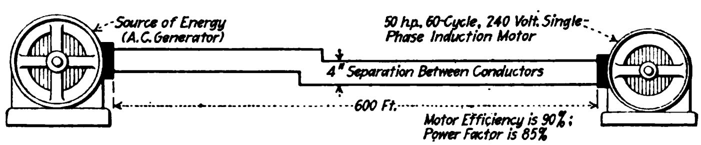


FIG. 118.—Another example in computing size of an alternating-current circuit conductor.

(Usually in solving practical motor-circuit examples the current can be read directly from tables.)

Actual watts = *apparent watts* $\times$ *p.f.* $= 48{,}758 \times 0.85 = 41{,}500$ *watts*.
Allowable energy loss is 4 per cent. $= 0.04 \times 41{,}500 = 1{,}660$ *watts*.

The size conductor that will give a 1,660-watt line loss with a line current of 195 amp. is found thus:

$$Cir.\ mils = \frac{I^2 \times 22 \times L}{P} = \frac{200 \times 200 \times 600 \times 22}{1{,}660} = 528{,}000{,}000 =$$
$$318{,}000\ cir.\ mils.$$

Try a 300,000-cir. mil conductor which safely carries 275 amp. Find the resistance and reactance drops in the line in the same way as in the preceding example, taking values for resistance and reactance of the 300,000-cir. mil cable from Table 190*A*.

$$I \times R = (200) \times \frac{0.075 \times 600}{1{,}000} = 9.0\ volts.$$

Then the percentage resistance drop $= 9.0 \div 240 = 3.75$ *per. cent.*

$$I \times X = (200) \times \frac{0.134 \times 600}{1{,}000} = 16.1\ volts.$$

Then the percentage reactance drop = 16.1 ÷ 240 = 6.7 *per cent.*

Now lay off this percentage resistance and reactance drop on the Mershon diagram of Fig. 115 (as shown in the enlarged view of Fig. 119) at the point, P, corresponding to 85 per cent. power factor, in the same man-

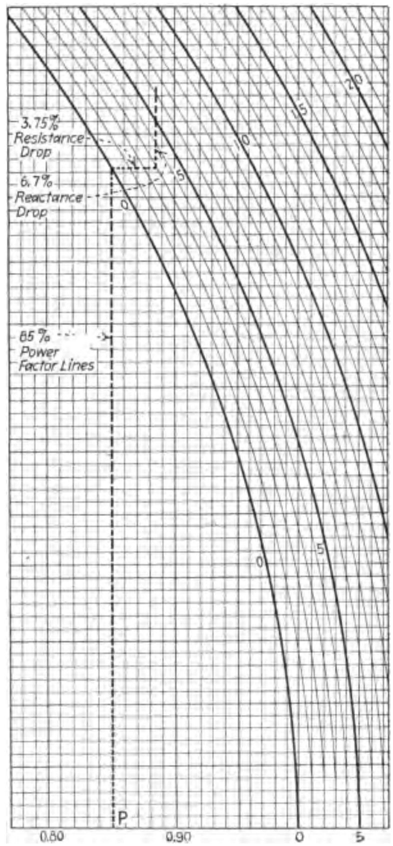


FIG. 119.—Mershon diagram solution of the problem of Fig. 115.

ner as in the above example. The true volts drop is found to be 6 per cent. Or, in actual volts, the true line drop is: 0.06 × 250 = 15 *volts.* This satisfies the requirements of the example.

192. The Determination of the Wire Size for Two-phase, Alternating-current Circuits may be made on this basis: *A four-wire, two-phase circuit may, so far as energy loss and voltage*

reactance drop are concerned, be replaced by two single-phase circuits identical (as to size of wire, distance between wires, current and e.m.f.) with two circuits of the two-phase transmission, provided that in both cases there is no inductive interaction between circuits. Therefore, to calculate a four-wire, two-phase circuit, compute the single-phase circuit required to transmit one-half the power at the same voltage. Then the two-phase transmission will require two such circuits.

193. The Determination of the Wire Size for a Two-phase, Alternating-current Circuit Where the Line Reactance Is Negligible may be based on the truth outlined in the preceding Art. 192. This method may, ordinarily, be used for interior wiring circuits and under the same conditions as specified in preceding articles for single-phase circuits. If the power-factor of the load is 100 per cent., the load balanced, and the line has no reactance the result obtained by using the equation given below will (assuming 11 ohms is the resistance of a circuit mil-foot of copper) be correct. If the power factor of the load is less than 100 per cent. and the line has no or very little reactance the true volts drop in the line will, as outlined in Art. 188, be something less than the volts drop represented by V in the following formulas.

Note.—In calculating a two-phase circuit by the method to be described, the first step (unless the current per phase is known) is to find one-half of the total power load fed by the circuit. Then find the current in amperes corresponding to this one-half total power load with a balanced two-phase four-wire circuit. The current corresponding to one-half the total load will be the current in the outside wires, hence, may be computed with the following formula:

$$I = 0.50 \times \frac{P}{E \times p.f.} \quad \text{(amperes)} \tag{61}$$

Wherein.—I = the line current, in amp. P = the actual power load in watts. E = the voltage impressed on the load. $p.f.$ = the power factor of the load.

When the current value, I, has been obtained with the above formula or if the current per phase, which is the same thing, is known it is substituted in formula (54) which is:

$$cir.\ mils = \frac{22 \times I \times L}{V}.$$

Wherein.—*Cir. mils* = area of conductors, four of which will be required. I = current in each phase, in amperes. L = single distance of the circuit, in feet. V = allowable volts drop in the circuit.

EXAMPLE.—What size wire should be used for the two-phase circuit of Fig. 120? The load consists of 55 kw. in incandescent lamps. The power factor is 100 per cent. The single distance is 300 ft. The allowable drop is 2 volts. Conductors are to be carried in conduit, hence line reactance will be small and can be neglected.

SOLUTION.—First find the line current (current per phase from formula (61) above) thus:

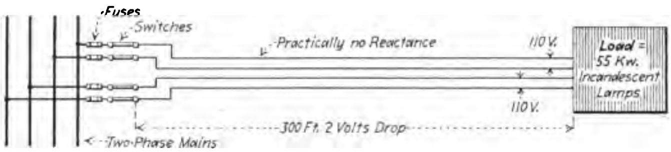


FIG. 120.—Size wire for two-phase circuit.

$$I = 0.50 \times \frac{P}{E \times p.f.} = 0.50 \times \frac{55 \times 1{,}000}{110 \times 1.0} = 0.50 \times \frac{55{,}000}{110} = 250\,amp.$$

Therefore, 250 amp. will flow in each wire. Now substitute in the formula (54):

$$cir.\ mils = \frac{22 \times I \times L}{V} = \frac{22 \times 250 \times 300}{2} = 875{,}000\ cir.\ mils.$$

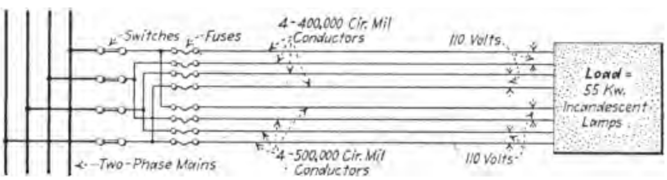


FIG. 121.—Arrangement of conductors for example of Fig. 120.

A 900,000-cir. mil cable might be used which would (from Table 190*A*) safely carry 600 amp. Four such cables would be required for the circuit. But a 900,000-cir. mil cable would be altogether too large to handle readily to draw into conduit. Furthermore, its skin effect* would be excessively large. Hence, the circuit should be split up and arranged into, possibly, one sub-circuit of four 400,000-cir. mil conductors and one sub-circuit of four 500,000-cir. mil conductors as suggested in Fig. 121. Cables of these sizes can be handled readily and their skin effects would be relatively small, particularly if they were made with fibre cores.* Checking with a table of safe-current-carrying capacities, it is evident that these conductors would be amply large to carry the current.

* See the author's PRACTICAL ELECTRICITY and AMERICAN ELECTRICIANS' HANDBOOK.

EXAMPLE.—What size wire should be used for the branch circuit to the 220-volt two-phase motor of Fig. 122? The motor is rated on its nameplate as taking 44 amp. per phase (if the ampere per phase is not given it can be computed from the formula given in the preceding example). The circuit is 110 ft. long. The allowable drop is 3 per cent. SOLUTION.—The allowable volts drop is: 0.03 × 220 = 6.6 or say 7 volts. Now substitute in formula (54):

$$Cir.\ mils = \frac{22 \times I \times L}{V} = \frac{22 \times 44 \times 110}{7} = \frac{106{,}480}{7} = 15{,}211\ cir.\ mils.$$

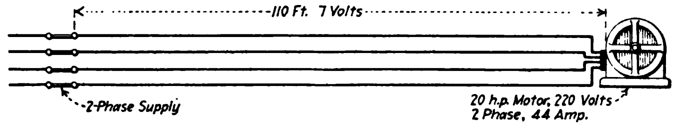


FIG. 122.—Find size wire.

From Table 190*A* the next larger standard wire size is No. 8 which has an area of 16,510 cir. mils and which will, with rubber insulation, safely carry 35 amp. This being a branch circuit to a motor, it must be capable of safely carrying at least a 25 per cent. overload: 1.25 × 44 = 55 *amp.* Hence, No. 4 wire, the smallest size which will safely carry 55 amp., must be used. Four No. 4 wires from the switch to the motor would constitute the circuit.

194. The Determination by the Graphic Method of the Wire Size for a Two-phase Circuit Where the Line Has Reactance may be made on the following basis. The computations are

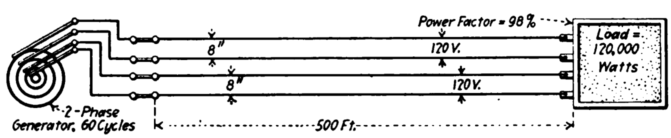


FIG. 123.—Find size wire for two-phase circuit.

based on the following methods which are similar to those for single-phase circuits where the line has reactance. They may, therefore, be made either graphically or with the Mershon diagram of Fig. 115. The first step is to find one-half the load on the circuit under consideration. Then proceed with the graphical or the Mershon diagram solution just as if the circuit were a single-phase circuit carrying this one-half load.

EXAMPLE.—What size wire should be used for the feeder of Fig. 123? It serves a two-phase load comprising twenty-four hundred 50-watt in-

candescent lamps. The power factor is 98 per cent. The circuit is 500 ft. long. The pressure at the load end of the feeder should be 120 volts. The conductors are supported, 8 in. between centers, on a pole line. The allowable energy loss is 10 per cent. of the energy transmitted. The true voltage drop in the line must not exceed 10 or 12 per cent. SOLUTION.—Find one-half of the total load thus: 2,400 *watts* × 50 *watts per lamp* = 120,000 *watts* is the total load. Now one-half the total load is: (120,000 *watts*) ÷ 2 = 60,000 *watts*.

From this point on the example is solved by precisely the same method as that illustrated in connection with Fig. 112 (the load in the present example was taken purposely just twice that of the Fig. 112 load to illustrate the principle). For this two-phase circuit with a 120,000-watt total load four 600,000-cir. mil conductors might be used and with them the true volts line drop would be 21 volts (Fig. 113) or the same as if two 600,000-cir. mil conductors were used with a 60,000-watt load on a single-phase circuit.

Since, however, a 12 per cent. drop should not exist in the circuit of this problem, each 600,000-cir. mil conductor can be split into two 300,000-cir. mil conductors in order to reduce the line reactance. With the conductors thus split up, as in the example of Fig. 121, the true volts line loss would be (Fig. 114) 14.5 volts or 12 per cent., which meets the conditions of this example. Eight 300,000-cir. mil conductors would then be required for this two-phase transmission and they should be arranged in a manner similar to that suggested in the example of Fig. 121.

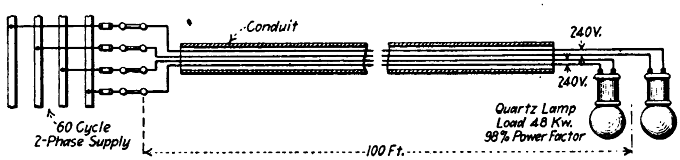


FIG. 124.—Find size wire and voltage drop.

195. The Determination, With the Mershon Diagram, of the Wire Size for a Two-phase Circuit Where the Line Has Reactance will now be explained. As with the graphic method described in the preceding article, the first step is to find one-half of the total load on the circuit. Then proceed with this one-half total load as if it were the entire load on a single-phase circuit.

EXAMPLE.—What size wire should be used for the two-phase feeder circuit of Fig. 124? The load consists of 48 kw. (48,000 watts) in quartz lamps. The circuit is 100 ft. long. The pressure at the receiver end of the circuit is to be 240 volts. The wires are carried in conduit. The power factor of the lamp load is 98 per cent. The frequency is 60 cycles.

The energy loss should not exceed 2 per cent. The volts line drop should not exceed 2 per cent. of the receiver voltage. SOLUTION.—First find one-half the total load, thus: (48,000) ÷ 2 = 24,000 *watts*. From this point on the example is solved in precisely the same manner as that of Figs. 116 and 117. (The load in the present example was taken purposely just twice that in the single-phase example of Fig. 116 in order to illustrate the principle.) The other conditions of the present two-phase example are the same as those of the single-phase example of Fig. 116.

For this two-phase circuit with a 48,000-watt total load four No. 1 wires should be used and with them the true-volt line loss will be about 1 per cent. or 2.4 volts—the same as in the two conductors of the single-phase circuit serving the 24,000-watt load in Fig. 116.

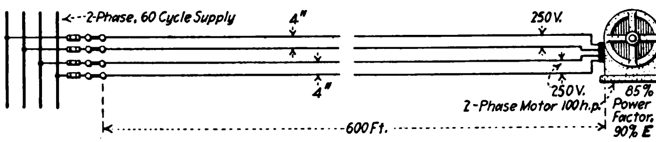


FIG. 125.—Find size wire and voltage drop.

EXAMPLE.—The result for the example of Fig. 125, which shows a 100-h.p. motor fed by a two-phase circuit, is the same as that for the example of Fig. 116 which shows a 50-h.p. motor fed by a single-phase circuit. All of the conditions, with the exception of the horse-power rating of the motor, are the same for both problems. The problem is worked out for Fig. 118 for the single-phase 50-h.p. load. The solution for the two-phase circuit with a 100-h.p. load (twice the single-phase load) is precisely the same as for the 50-h.p. single-phase load, after one-half of the two-phase load has been found thus: (100 *h.p.*) ÷ 2 = 50 *h.p.* However, two 300,000-cir. mil conductors are used for the 50-h.p. single-phase circuit and four 400,000-cir. mil conductors are used for the 100-h.p. two-phase circuit.

196. The Determination of the Wire Size for a Three-phase Circuit Where the Line Reactance Is Small and may, therefore, be disregarded, may be made with the following formula, the derivation for which is given in the following note:

$$\text{(62)} \qquad cir.\ mils = \frac{19 \times I \times L}{V} \qquad \text{(circular mils)}$$

$$\text{(63)} \qquad V = \frac{19 \times I \times L}{cir.\ mils} \qquad \text{(volts)}$$

$$\text{(64)} \qquad I = \frac{V \times cir.\ mils}{19 \times L} \qquad \text{(amperes)}$$

$$L = \frac{V \times cir.\ mils}{19 \times I}. \qquad \text{(feet)} \tag{65}$$

Wherein: *Cir. mils* = area, in circular mils, of each of the three wires of the balanced three-phase circuit. I = the current, in amperes, in each of the three wires. L = the single distance or length one way of the circuit in feet. V = the allowable drop, in volts, in the line.

197. The Conditions Under Which the Above Three-phase Formulas May be Used can be specified thus: they are ordinarily sufficiently accurate for interior-wiring circuits and, under the conditions as specified in Art. 186, for single-phase circuits of small line reactance. If the power factor of the load is 100 per cent., the load balanced and the line has no reactance, the result given by the preceding formulas will be theoretically correct, assuming the resistance of a circular mil-foot of copper is 11 ohms. If the power factor of the load is less than 100 per cent. and the line has no or very little reactance the true volts drop in the line will be something less than the volts drop represented by V in the preceding equations; see Fig. 108 for an illustration of the principle as applied to single-phase circuit.

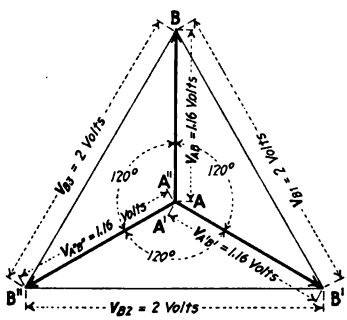


FIG. 126.—Showing vector relations of drops in a balanced three-phase circuit.

NOTE.—*The Derivation of the Above Formulas for Determining Three-phase Wire Sizes Where Line Reactance May Be Disregarded.*—The voltage relations in a three-phase circuit may be represented by the diagram shown in Fig. 126. The values in this particular diagram apply to the circuit diagrammed in Fig. 127. This diagram (Fig. 127) shows how voltmeters would read if connected to the three-phase circuit there diagrammed. The voltage impressed on the circuit is 110 volts. The drop in each of the three line wires, AB, A^1B^1 and $A^{11}B^{11}$ is 1.16 volts. From this it might be assumed that the voltage impressed on the load would be: 110 − 1.16 = 108.84 *volts;* however, such is not the case. The volt-

age between wires at the load would actually be, as shown in the picture, 108 volts.

The reason for this is that the e.m.fs. in AB, A^1B^1 and $A^{11}B^{11}$ are not in phase with one another. Hence, the voltage drops in these three conductors are not in phase with one another. Since the e.m.fs. in the three wires of the three-phase circuit differ in phase by 120 deg. if there is a drop of 1.16 volts in each of the conductors the total drop across any two of the conductors will be (as shown in Fig. 126) $1.16 \times 1.73 = 2$ *volts.*

Now, the drop in one of the wires of a balanced three-phase circuit (for example AB, Fig. 127) may be computed from formula (46):

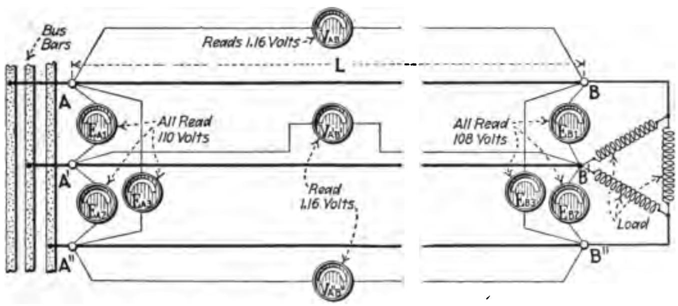


FIG. 127.—Illustrating drop in voltage in a three-phase circuit.

$$V = \frac{11 \times I \times L}{cir.\ mils}.$$

The drop obtained by the above equation is sometimes called "the drop to neutral." Now it is evident from Fig. 126 that the drop in any two of the conductors of a three-phase circuit, for example in AB and A^1B^1 (Fig. 127) would be: $1.73 \times$ *the drop in one of the conductors.* Thus the total drop in the two conductors may be expressed thus:

$$V = \frac{11 \times I \times L \times 1.73}{cir.\ mils} = \frac{19 \times I \times L}{cir.\ mils}$$

Hence, from the above equation it follows that for a three-phase circuit:

$$Cir.\ mils = \frac{19 \times I \times L}{V}.$$

EXAMPLE.—What size wire should be used for the circuit to the three-phase 220-volt motor of Fig. 128? The circuit is 400 ft. long. It is carried in conduit so that the line reactance is negligible. The allowable drop is 6 volts. The motor takes 40 kw. It is assumed that its power factor is but 70 per cent. First, find the current thus (for the derivation of the following formula, see the author's AMERICAN ELECTRICIANS' HANDBOOK or his PRACTICAL ELECTRICITY):

$$I = \frac{kw. \times 580}{E \times p.f.} = \frac{40 \times 580}{220 \times 0.7} = 151\ amp.$$

Now substitute in the above formula (62):

$$cir.\ mils = \frac{19 \times I \times L}{V} = \frac{19 \times 151 \times 400}{6} = 191{,}266\ cir.\ mils.$$

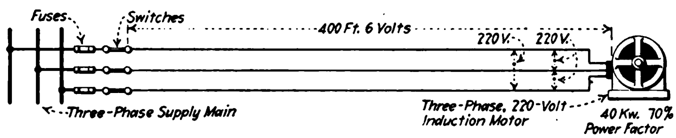


FIG. 128.—Find wire size for three-phase circuits.

Referring to Table 190*A*; the next larger wire size is No. 000 which has an area of 211,600 cir. mils. Since this is a motor circuit, it must be capable of carrying a current overload of at least 25 per cent., hence this circuit must be capable of safely handling: 151 × 1.25 = 188.8 *amp.* Now No. 0000 will safely carry 225 amp. with rubber insulation or 325 with other insulations, which is satisfactory as a conductor for this example.

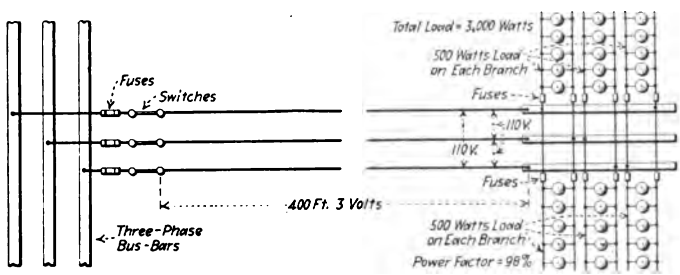


FIG. 129.—Find wire size for three-phase circuit.

EXAMPLE.—What size conductor should be used for the three-phase, 110-volt feeder circuit of Fig. 129? The load consists of 3 kw. (3,000 watts) of incandescent lamps at a power factor of 98 per cent. The wires are strung close together so that the line reactance can be neglected. The circuit is 400 ft. long and the allowable drop is 3 volts. SOLUTION.—First find the current which would flow in this circuit.

$$I = \frac{kw. \times 580}{E \times p.f.} = \frac{3 \times 580}{110 \times 0.98} = 16.2\ amp.$$

Now substitute the above current value in formula (62) thus:

$$cir.\ mils = \frac{19 \times I \times L}{V} = \frac{19 \times 16.2 \times 400}{3} = 41{,}040\ cir.\ mils.$$

The next larger wire size (referring to Table 190*A*) is No. 4, which has an area of 41,740 cir. mils. This conductor will more than safely carry the 16.2 amp. of this example, hence is safe and may be used.

198. A Three-wire Three-phase Transmission May Be Replaced by Two Single-phase Circuits.—It is frequently desirable to utilize this fact in making three-phase circuit wiring calculations, particularly where the three-phase circuit has reactance. That is, a three-wire three-phase transmission having conductors symmetrically located may, so far as energy loss and voltage requirements are concerned, be replaced by two single-phase circuits having no inductive interaction and identical with a three-phase line as to size of wire and distance between wires. Therefore, to calculate a three-phase transmission calculate a single-phase circuit to carry one-half the load at the same voltage. The three-phase transmission will require three wires of the size and distance between centers as obtained with the single-phase transmission.

199. The Determination of the Wire Size for a Three-phase Circuit Where the Line Has Reactance may be made either graphically or with the Mershon diagram (Fig. 115). Where either the Mershon or the graphical method is used the fact outlined in Art. 198, *that a three-phase circuit can be replaced by two single-phase circuits,*" is utilized. Regardless of whether the Mershon or graphical method is used, first find one-half of the total load. Then proceed with the problem using this one-half total load just as if it were fed by one single-phase circuit. The method of solving three-phase problems is similar to that used for the two-phase examples above given, except that three wires of the size obtained are used for three-phase circuits, whereas four wires are used for the two-phase circuits.

EXAMPLE.—What size conductor should be used for the open-wire transmission shown in Fig. 130? The allowable volts loss in the line is 4 per cent., or $0.04 \times 220 = 8.8$ *volts*. Receiver voltage = 220. Load = 50 kw. Power factor = 0.80. Distance between wires = 3 in. Frequency is 25 cycles. SOLUTION.—The actual current in each wire must be known to insure that a conductor large enough to carry it will be selected.

$$Actual\ current = \frac{0.58 \times p}{E \times p.f.} = \frac{0.58 \times 50{,}000}{220 \times 0.8} = \frac{29{,}000}{176} = 165\ amp.$$

Now find one-half of the total load and proceed with this load as for a single-phase transmission which will be called the imaginary transmission.

$$\tfrac{1}{2}\ total\ load = \frac{watts}{2} = \frac{50{,}000}{2} = 25{,}000\ watts.$$

The current in the imaginary transmission would be:

$$I = \frac{p}{E \times p.f.} = \frac{25{,}000}{220 \times 0.80} = \frac{25{,}000}{176} =$$

142 *amp.* in the imaginary transmission.

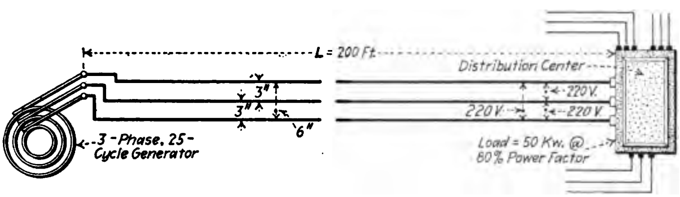


FIG. 130.—Example in determining wire size for a three-phase feeder.

To approximate the size of wire, use the single-phase formula (54):

$$Cir.\ mils = \frac{22 \times I \times L}{V} = \frac{22 \times 142 \times 200}{8.8} = \frac{624{,}800}{8.8} = 71{,}000\ cir.\ mils.$$

The next larger standard size wire is No. 1—83,690 cir. mils—which will safely carry, when exposed, 150 amp. The actual current is 165 amp. No. 1 is, therefore, not satisfactory from a current-carrying standpoint. Hence, it will be necessary to use the next larger size wire, No. 0, which will safely carry, when exposed, 185 amp. Now check this No. 0 wire for volts line drop.

The average distance between the three wires =

$$\frac{3\ in. + 3\ in. + 6\ in.}{3} = \frac{12\ in.}{3} = 4\ in.$$

Refer to Table 190*B* under 25 cycles and opposite No. 0 wire and find: Resistance volts per 1,000 ft. = 0.196 and (under 4-in. separation) reactance volts per 1,000 ft. = 0.066. Then:

$$\textit{Resistance drop} = \frac{\textit{current} \times \textit{resist. volts} \times \textit{dist.}}{1{,}000}$$

$$= \frac{142 \times 0.196 \times 200}{1{,}000} = 5.57 \textit{ volts.}$$

$$\textit{Per cent. resistance drop} = \frac{5.57}{220} = 2.5 \textit{ per cent.}$$

$$\textit{React. drop} = \frac{\textit{current} \times \textit{react. volts} \times \textit{dist.}}{1{,}000}$$

$$= \frac{142 \times 0.066 \times 200}{1{,}000} = 1.87 \textit{ volts.}$$

$$\textit{Per cent. reactance drop} = \frac{1.87}{220} = 0.85 \textit{ per cent.}$$

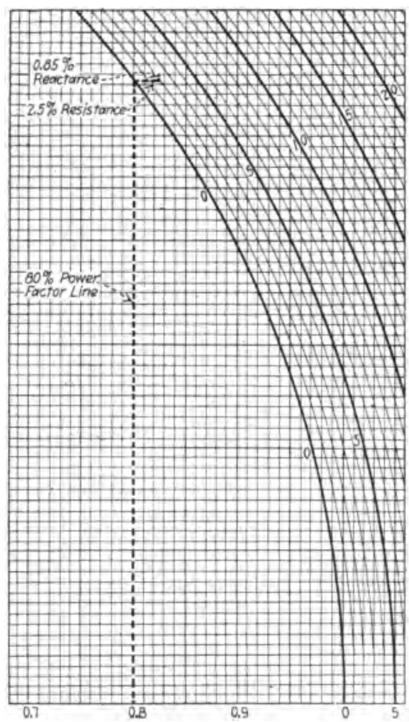


FIG. 131.—Illustrating the application of the Mershon diagram for computing a three-phase, three-wire alternating-current circuit.

Laying out the per cent. resistance drop and the per cent. reactance drop on the Mershon diagram (Fig. 131): At the upper end of the 80 per cent. power-factor line as described previously, the last point of the

layout comes just under the 3 per cent. volts loss circle. Therefore, the true volts drop in the line will be somewhat less than 3 per cent. with No. 0 wire. Therefore, use three No. 0 wires for the transmission as shown in Fig. 130.

200. The Determination of the Wire Size of Single-phase Branches Fed From Three-phase Mains can be made by using

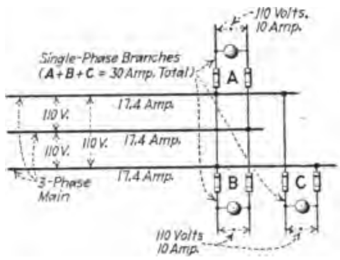


FIG. 132.—Current in three-phase main and single-phase branch.

the direct-current formula. The branch circuit is treated as if it were an independent single-phase circuit.

NOTE.—Fig. 132 shows the relation of the total current in a three-phase main to the total currents taken by the several single-phase branch circuits feeding from it. The three-phase circuit current is equal to the total of the single-phase circuit currents multiplied by 0.58. Thus for the problem of Fig. 132: 30 *amp.* × 0.58 = 17.4 *amp.*

SECTION 10

TRANSMISSION AND DISTRIBUTION OF ELECTRICAL ENERGY

201. The Reason Why Energy Is Transmitted Electrically, particularly where large amounts are to be transmitted over long distances, is that the electrical method is the most economical, convenient, simple and satisfactory one available for the applications for which it is so widely used.

NOTE.—Energy may be transmitted satisfactorily and in some cases most economically by steam, compressed air, line shafts, belt and rope drives and by similar methods. But it is obvious that any of the methods just mentioned would be wholly inadequate, impracticable and uneconomical for transmitting large amounts of energy over long distances.

202. A High Voltage Is, From a Standpoint of Pure Economics, Desirable for the Transmission or Distribution of Electrical Energy.—However, features of safety and utility often render desirable or necessary the use of relatively low voltages. Why a high voltage is desirable economically will be evident from a consideration of the articles which immediately follow.

203. The Power Lost in an Electrical Circuit Transmitting a Given Load Varies Inversely as the Square of the Impressed Voltage.—(Certain factors which affect only very-high-voltage, alternating-current lines are disregarded.) If the voltage impressed on a line is doubled the watts line loss—a certain given amount of power being transmitted—will be quartered. If the impressed voltage is trebled the loss will be one-ninth of that with the original voltage. Note the following example:

EXAMPLE.—Refer to Fig. 133. In both *I* and *II* the same line is shown. It is of No. 10 B. & S. gage copper wire, which has a resistance of approximately 1 ohm per 1,000 ft., so the entire circuit (10,000 ft. of wire) will have a resistance of about 10 ohms. The load at the end of the line is, in each case, 5 kw. Since the apparatus at the end of each of the lines is designed for operation on 200 volts, that pressure, approximately, must be maintained at the receiving end of each line.

In system *I*, the motor is connected directly to the line. Hence, the current taken by the motor (which will be: 5,000 *watts* ÷ 200 *volts* = 25 *amp.*) will flow in the line. From the Ohm's law formulas, the voltage drop in the line for system *A* will be: $E = I \times R = 25 \times 10 = 250$ *volts*. And the power loss in the line will be: $P = I^2 \times R = 25 \times 25 \times 10 = 6{,}250$ *watts*.

This means that the generator voltage would have to be equal to: (*volts impressed on receiver*) + (*volts loss in line*) = 200 + 250 = 450 *volts*. Note also that a certain amount of power—6,250 watts—is lost, dissipated as heat, in the line. This necessitates that the generator *A* develop 11,250 watts, 6,250 watts more than is delivered to the motor. Obviously, the transmission system of Fig. *I* is not an economical one because more power is lost in the line than is delivered to the motor.

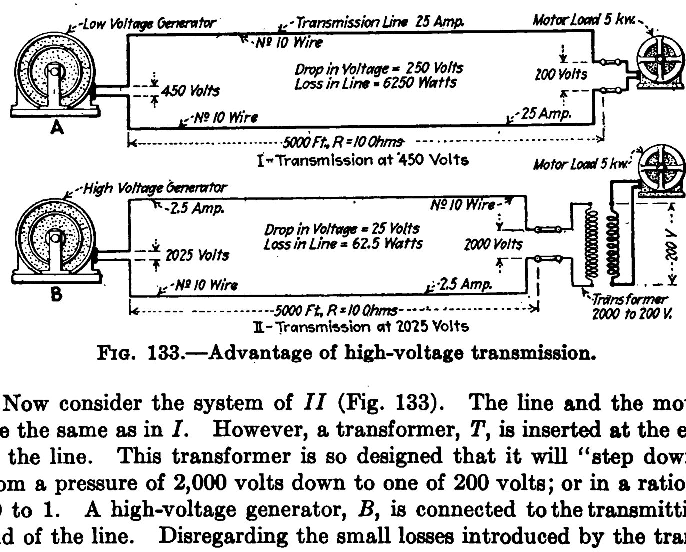


FIG. 133.—Advantage of high-voltage transmission.

Now consider the system of *II* (Fig. 133). The line and the motor are the same as in *I*. However, a transformer, *T*, is inserted at the end of the line. This transformer is so designed that it will "step down" from a pressure of 2,000 volts down to one of 200 volts; or in a ratio of 10 to 1. A high-voltage generator, *B*, is connected to the transmitting end of the line. Disregarding the small losses introduced by the transformer, the current in the line will be: (5,000 *watts*) ÷ (2,000 *volts*) = 2.5 *amp.*

From the Ohm's law formula, the voltage drop in the line for system *B* will be: $E = I \times R = 2.5 \times 10 = 25$ *volts*. The power loss in the line will now be: $P = I^2 \times R = 2.5 \times 2.5 \times 10 = 62.5$ *watts*.

The generator voltage would have to be: 2,000 + 50 = 2,050 *volts*. The power loss in the line is now only 62.5 watts. Now note that by increasing the voltage 10 times, from 200 to 2,000 volts, *the line loss was decreased* 100 *times*. This example shows why the power loss in a line varies inversely as the square of the impressed voltage. It was decreased from 6,250 watts to 62.5 watts. The use of alternating current in *B*

would make the actual results slightly different from those obtained in the solutions above, but the difference would not be of any practical consequence insofar as the general principle described is concerned. See the author's *American Electricians' Handbook* for an example tabulated in detail showing the effect of different transmission voltages in transmitting 30 kw. over a line of 3 ohms resistance.

204. The Weight of a Conductor Is, for a Given Power Loss, Inversely Proportional to the Square of the Impressed Voltage. —The truth of this statement may be readily verified by solving simple examples similar to these above given.

205. For Short Transmission Distances a High Voltage is Seldom Desirable because, although the cost of the copper in a transmission line would (with a given watts power loss) be less than if a low voltage were used, there are other considerations which more than offset this cost. With a high voltage, the generator is frequently more expensive. Furthermore, costly transformers, to reduce the voltage at the receiving end of the line must, ordinarily, be used for incandescent lighting and also for motors which are located inside of buildings where a high voltage would be dangerous. In special cases relatively-high-voltage motors may be connected direct to transmission lines of corresponding voltages.

206. The Efficiency of Transmission of an Electrical Circuit is similar to any other kind of efficiency in that it is the ratio of output to input. The power delivered at the receiving or far end of any electrical circuit is always less than the power delivered to the circuit, by an amount equal to the losses in the line. The line loss is almost wholly (and for practical purposes may be considered as being entirely) the $I^2 \times R$ power loss.

NOTE.—Theoretically, by using a sufficiently large conductor, the losses may be reduced to practically zero, that is the efficiency may be increased to almost 100 per cent. But in practice nothing is gained by using an excessively large conductor. If the conductor is too large, the interest on the money invested in it will more than offset the cost of the energy saved by using the large conductor. In practice transmission circuits are frequently so designed that they are about 90 per cent. efficient; that is, the line power loss is about 10 per cent. It is impossible (Fig. 134) to have a circuit which is exactly 100 per cent. efficient regard-

less of how large—of how little resistance—its conductors are. In designing circuits* every case should be treated on its merits.

207. To Compute the Efficiency of a Transmission Line or circuit, a formula based on the preceding statements may be used. In general: *efficiency = output ÷ input.* Stating the same thing in another way: *efficiency = (output) ÷ (output + losses).* Now, restating this to apply to a transmission line:

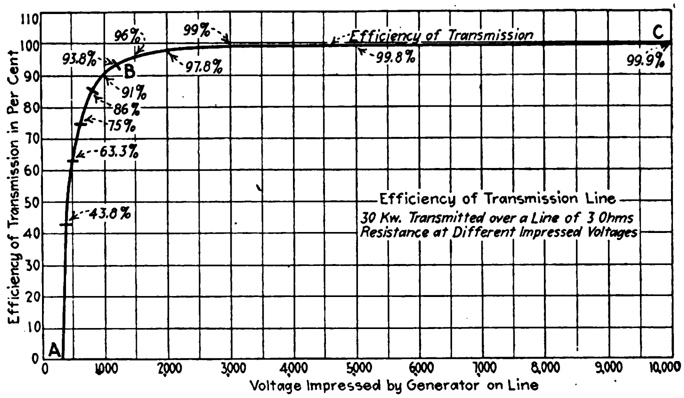


FIG. 134.—Graph showing increase of transmission efficiency with the transmission voltage. (The values plotted above relate to the specific problem designated. Note that in this particular example the efficiency of transmission increases very rapidly with increase of impressed voltage until the pressure is (at *B*) above 1200 or 1500 volts. Above this pressure efficiency increases much more slowly. Even at *C*, for a pressure of 10,000 volts, the efficiency is only 99.9 per cent.)

$$(66)\quad \textit{Effi. of transmission} = \frac{\textit{power delivered by line}}{\textit{power received by line}} \text{ (per cent.)}$$

or modified:

$$(67)\quad \textit{Efficiency of transmission} = \frac{\textit{power del. by line}}{(\textit{power del. by line}) + (\textit{power losses in line})}.$$

EXAMPLE.—What is the efficiency of the circuit of Fig. 135 under the conditions there noted? The impressed e.m.f. is 112 volts. The current is 800 amp. The resistance of each line conductor is 0.006 ohm. SOLU-

* See article headed "The Question of Energy Loss in a Circuit" in the author's AMERICAN ELECTRICIANS' HANDBOOK.

TION.—*Power received by the line* $= I \times E = 800 \times 112 = 89{,}600$ *watts.* *Power lost in line* $= I^2 \times R = 800 \times 800 \times 0.012 = 7{,}680$ *watts.* Hence, *power delivered by line* $= 89{,}600 - 7{,}680 = 81{,}920$ *watts.* Now substitute in formula (66):

$$Eff.\ of\ trans. = \frac{power\ del.\ by\ line}{power\ rec.\ by\ line} = \frac{81{,}920}{89{,}600} = 0.913 = 91.3 \text{ per cent.}$$

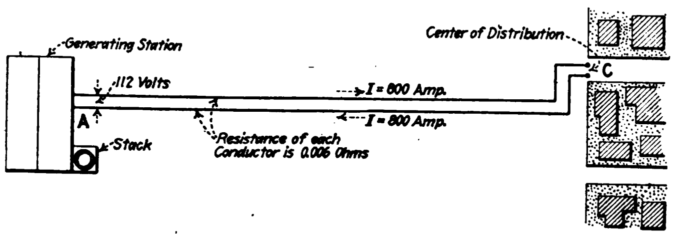


FIG. 135.—Example in computing efficiency of transmission.

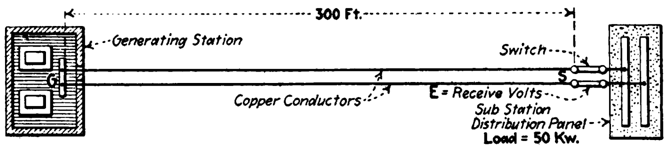
208. Direct Current for Transmission and Distribution is with multiple circuits, ordinarily, suitable only where the distances involved are not great. Direct-current voltages can be "stepped up" or down only by using motor generators which are expensive in first and operating costs. Hence, the economics of the situation dictate that, as a rule, the receivers —lamps and motors—on direct-current multiple circuits must operate at the voltage which is impressed on the circuit by the direct-current generator.

Because of the fact that multiple incandescent lamps designed for operation on, approximately, 110 volts are more economical in first and operating costs than lamps for higher voltages this pressure, 110 volts, is practically standard for incandescent-lighting circuits. Lamps for voltages lower than 110 would of themselves be satisfactory, but the cost of the large conductors which would be necessary to serve low-voltage lamps with energy would be prohibitive. The result is that the pressure on any circuit used for incandescent lighting is, in effect, limited to approximately 110 volts. Obviously this pressure is not sufficiently high for economically transmitting energy over considerable distances.

209. Relatively-high-voltage Direct-current Transmission and Distribution is satisfactory and economical where the load

is mainly power (motors) rather than multiple incandescent lighting. Direct-current pressures as high as 1,500 and 3,000 volts have been applied successfully for electric railway work. In industrial plants 550 volts, direct current, has been used to some extent for motors and cranes; higher voltages are undesirable for general distribution within buildings or plants, because of the danger to human life that they involve.

NOTE.—Voltages lower than 550 may be fatal. Where the contact with the body is good or where the person has a weak heart, a voltage as low as 110 may kill.



Property	E_1 = 110 Volts	E_2 = 220 Volts
I = *Current in the Line*	$= \frac{50 \times 1000}{110} = 455$ *Amp.*	$= \frac{50 \times 1000}{220} = 227$ *Amp.*
V = *Voltage Drop in Line*	= 2.5% *of* 110 = 2.75 *Volts*	= 2.5% *of* 220 = 5.5 *Volts*
R = *Resistance of Line*	$= \frac{V}{I} = \frac{2.75}{.455} = 0.006$ *Ohms*	$= \frac{V}{I} = \frac{5.5}{227} = 0.024$ *Ohms*
Cir. Mils = *Area of Wire*	$= \frac{22 \times L}{R} = \frac{22 \times 300}{0.006} = 1{,}100{,}000$ *c.m.*	$= \frac{22 \times L}{R} = \frac{22 \times 300}{0.024} = 275{,}000$ *c.m.*

FIG. 136.—Comparison of 110- and 220-volt transmission, adapted from Gray. (This table shows the solution of a problem where 50 kw. must be transmitted 300 feet with a 2.5 per cent. drop and where it is required that the conductor size be known for a receiver pressure of 110 volts and also 220 volts. The resistivity of copper is taken as 11 ohms per circular mil foot. Note that since, with the same per cent. line loss and the same load, the conductor area varies inversely as the square of the transmission voltage, the area with E = 110-volts is four times that with E = 220 volts. In other words, by doubling the pressure the conductor area has been quartered.)

210. Three-wire Distribution is now used in practically all installations of any consequence where multiple incandescent lamps are to be served. With the three-wire system, 110-volt lamps may be used on the side circuits while the energy is, in effect, transmitted by the outside wires at 220 volts. Thereby the economics of 220-volt transmission (see Fig. 136) are utilized. The neutral wire may be small where the load on the three-wire circuit is well balanced. The consequence is

that the weight of copper conductor required for a three-wire system will be only a quarter to three-eighths of that necessary for an equivalent two-wire system.

211. Standard Direct-current Voltages and Their Applications.

Voltages: Generators and energy-delivering apparatus	Voltages: Motors and energy-utilization apparatus	Applications
*125	110	Used for multiple-circuit, incandescent lighting. Usually obtained from a 110–220-volt three-wire system.
*125–*250 575–*600	110– 220 *115–*230 *550	Direct-current motors.
*600	....	Urban and interurban electric railways.
1,200 1,500	....	Interurban railways.
2,400 3,000	....	Trunk line railways.

* Electric Power Club standard voltage ratings.

NOTE.—VOLTAGES, SYSTEMS AND FREQUENCIES IN USE IN THE UNITED STATES.—According to a recently published electrical directory of the United States,* there are no less than 4,700 central stations in towns of less than 50,000 inhabitants. An analysis of the data relative to 576 systems in six representative States indicates that 15 per cent. use direct current at voltages of 125, 250 and 550 volts two-wire, and 125 to 250 volts three-wire. How well some of these direct-current systems are applied is not apparent, but it is evident that the voltage of direct-current systems is quite well standardized. Of the total number of systems analyzed, 85 per cent. employed alternating current in 22 different combinations of number of phases, wires, cycles and volts, practically none of which are convertible into another combination without great difficulty and expense.

* A. J. Goedjen in a paper read before a joint meeting of the Electrical Section of the Western Society of Engineers and the Chicago Section of the American Institute of Electrical Engineers.

In the 488 alternating-current systems analyzed, 24 per cent. were single-phase, 13 per cent. three-wire two-phase, 1 per cent. four-wire two-phase, 39 per cent. three-wire three-phase, and 23 per cent. four-wire three-phase. Of these 488 systems, classified according to the voltages, 2 per cent. operate at 115 volts, 17 per cent. at 1,100 volts, 58 per cent. at 2,200 volts and 24 per cent. at 4,000 volts. The frequencies at which the 488 systems operate show even a greater diversity, 2 per cent. being 25-cycle, 0.6 per cent. 40-cycle, 90 per cent. 60-cycle, 0.2 per cent. 116-cycle, 1 per cent. 125-cycle, and 6.2 per cent. 133-cycle. The 116-, 125- and 133-cycle systems are small plants.

212. Alternating-current Transmission and Distribution Systems (Figs. 1 and 137) are not, in general, restricted by distance conditions. It is economically feasible to transmit almost any value of power over any reasonable distance with alternating current. Hence, where it is necessary that power be transmitted further than a mile or so or be distributed over a wide area for general light and power service the alternating-current system is always* adopted—because it is far more economical than a direct-current system. The cost of a multiple-circuit, direct-current long distance transmission and distribution system would be prohibitative.

213. The Reason Why Alternating Current Is in General, Preferable for Transmission and Distribution is that the voltages may be transformed ("stepped up" or "stepped down") with stationary transformers. These transformers are relatively low in cost, and are very efficient in operation. They have no moving parts hence require no attendance and may be installed out of doors, in manholes or on poles. Hence, energy may be generated at the most convenient voltage, increased, with a step-up transformer, to a pressure high enough for economical transmission or distribution and then lowered at the distant end of the line, with a "step-down" transformer to a voltage or voltages suitable for effective utilization.

EXAMPLE.—Figs. 1 and 138 show typical three-phase systems. In the system of Fig. 138 energy is generated by the alternator G at 2,200 volts. The voltage is "stepped up" by transformers T_u, located in the

* See the author's AMERICAN ELECTRICIANS' HANDBOOK for table showing Copper Economics of different distribution systems.

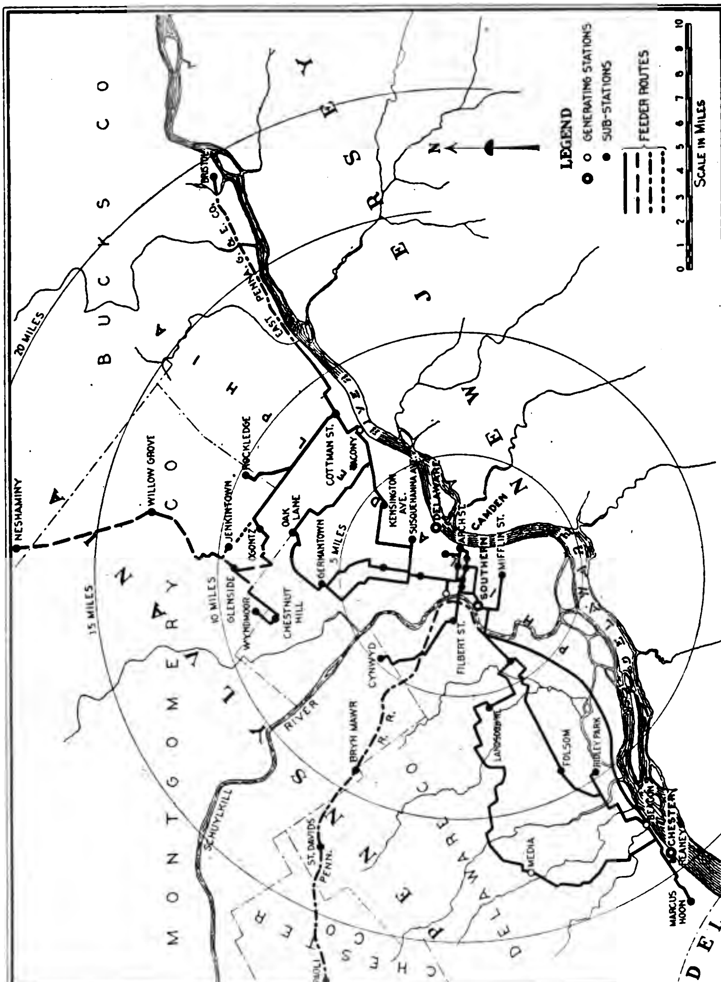


FIG. 137.—The distribution system of the Philadelphia, Pa. Electric Company.

generating station, to 50,000 volts which is the transmission pressure. The energy is then transmitted at 50,000 volts from the generating station (L_1) over the transmission line for a distance of possibly 25, 50 or 100 miles, to the receiving station (L_2). At the receiving station the pressure is stepped down with stationary transformers to 13,200 volts at which pressure it is distributed to substations, which may be of any one of the four types enumerated below or a combination thereof.

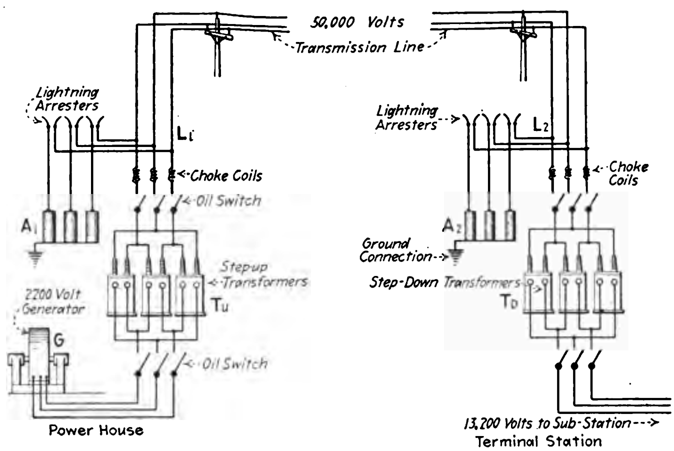


FIG. 138.—The elements of a high-voltage alternating-current electrical energy transmission system.

214. Three-phase Transmission Is Used in Preference to Single-phase or Two-phase because it is more economical of copper.* If a single-phase, two-wire transmission operating at a certain voltage requires a certain amount (or 100 per cent.) of copper, an equivalent two-phase, four-wire transmission will also require 100 per cent. An equivalent three-wire, three-phase transmission will require only 75 per cent. of the copper. A four-wire, three-phase transmission with the neutral the same size as the outers will require only 33.3 per cent.

* See the author's AMERICAN ELECTRICIANS' HANDBOOK for table showing Copper Economics of different distribution systems.

215. Standard Alternating-current Voltages and Their Applications.

Voltage: Generators and energy-delivering apparatus	Voltage: Motors and energy-utilisation apparatus	Application
120 *240	*110	Single-phase, used for small motors and lighting, usually obtained from a 120–240-volt three-wire system.
*240 *480 *600	*110–*220 *440–*550	Usually three-phase, used for distribution for power for polyphase motors up to possibly 50 to 60 h.p. output.
*1,200– *2,400 1,150 2,300	*440–*550 *1,100–*2,200	Usually three-phase, used for polyphase motors of capacities greater than about 50 to 60 h.p.
2,300–4,000 *2,400–4,150	....	For three-phase four-wire distribution in cities, 4,000 volts between outer wires and 2,300 volts between outer wire and neutral.
†13,200 See footnote *A*.	....	Highest pressure for which generator or motors can, ordinarily, be effectively designed. Often better to generate at 2,200 volts and then stop up with transformers to transmission line voltage.
† 6,600 †11,000 †13,200 †16,500 †22,000	The voltages higher than 13,200 are used for transmission only and not for generation	For power transmission over relatively short distances and where cable must be used.
†22,000 †33,000 †44,000 †66,000 †88,000 †110,000 †150,000		For long-distance power transmission over aerial lines. See "Thousand Volts Per Mile" article below.

A. Generators are sometimes built for 4,000, 6,600 and 11,000 volts.
* Electric Power Club standard voltage ratings.
† These voltages standardized by the National Electric Light Association and the Electric Power Club.

216. About a Thousand Volts Per Mile Length of Transmission* is a thumb rule which serves as an index. This is based on the fact that with copper conductors a pressure of 1,000 volts per mile, and a current density of 1 amp. per 1,000 cir. mils, the energy loss will be about 10 per cent. That is, a line designed on this basis will carry its current without excessive heating at about a 10 per cent. loss. For relatively short lines transmitting considerable power the rule provides a conductor too small for most economical operation, that is for minimum annual costs. Hence, for the short distance transmission of much power, a pressure greater than 1,000 volts per mile may be the more economical. Where a transmission system serves an extensive distance and the load is small a voltage smaller than "1,000 per mile" may sometimes be adopted with economy.

217. The Standard Frequency† in the United States may now be said to be 60 cycles. It appears that it is desirable, in practically every case, to adopt this rather than any other frequency. The economies and advantages that were expected to result from the use of 25 cycles for electrical energy transmission have not, in general, materialized. A number of plants which generate at 25 cycles have been constructed which necessitates the installation of 25- to 60-cycle frequency changers where 60 cycles is the utilization frequency.

NOTE.—Synchronous converters as formerly designed would not operate satisfactorily at frequencies much above 40 cycles. This was one of the reasons for the original installation of a number of 25-cycle generating stations. Motors for 25 cycles are, generally, except very slow-speed machines, more expensive than those for 60 cycles. Arc lights can not be used on 25 cycles. With incandescent lamps there is a noticeable flickering on 25 cycles which produces eye fatigue. This renders its application undesirable for interior illumination but it can be used for incandescent street lighting.

218. Sub-stations May, in General, Be Divided into Four General Classes: (1) Transformer sub-stations, (2) rotary-

* H. B. Gear.

† See the author's AMERICAN ELECTRICIANS' HANDBOOK, his PRACTICAL ELECTRICITY and his ELECTRICAL MACHINERY for further information on this subject.

converter sub-stations; (3) motor-generator sub-stations, and (4) frequency-changer sub-stations.

218A. The Function of a Sub-station Equipment is to so modify the characteristics of the energy received by it that the energy will then be suitable for utilization by that load which the sub-station serves. That is, the voltage may be lowered in the sub-station and a conversion made from alternating to direct current, if necessary, as will be described. So that each sub-station may most economically serve its load it should be located at or near the electrical center of the district served.

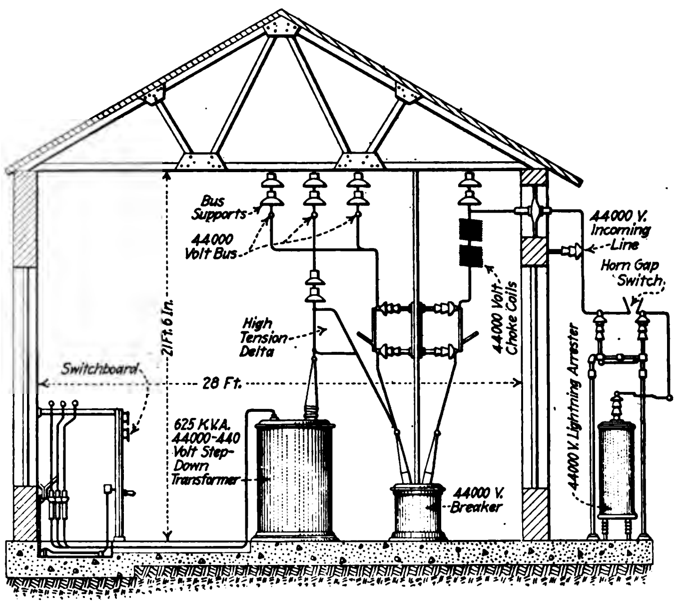


FIG. 139.—Typical transformer sub-station.

219. A Transformer Substation (Fig. 139) is one in which the alternating-current voltage is lowered, with step-down transformers, from the transmission voltage to one suitable for distribution to the consumers or to the power load. Usually the distribution primary feeders operate at 2,200 volts. Hence, the low-tension side of the step-down transformer

develops this voltage. A potential or feeder regulator,* which may be automatic or non-automatic, is usually inserted in each feeder to maintain the voltage at the distant end of the feeder practically constant. In a transformer sub-station the pressure is transformed from one voltage to another but the energy is not converted from alternating to direct current or the reverse.

220. In a Synchronous or Rotary Converter Sub-station (Figs. 140 and 141) conversion from alternating to direct cur-

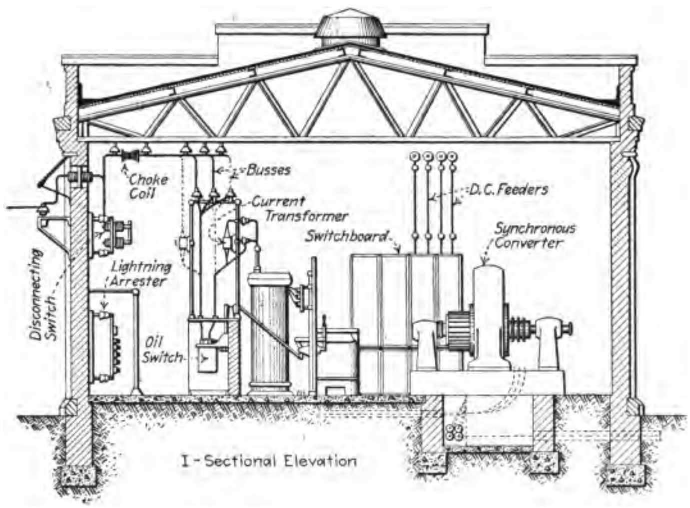
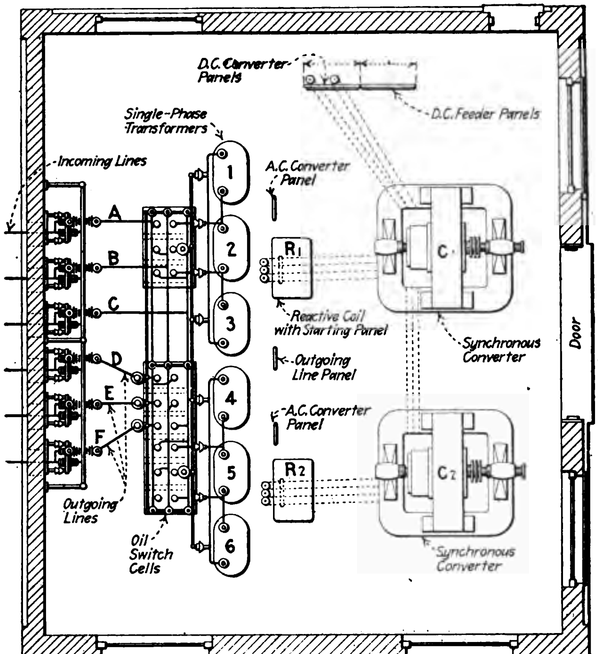


FIG. 140.—Sectional elevation showing typical arrangement of a synchronous converter sub-station for electric railway service.

rent is effected. Usually the voltage must be decreased with a transformer on the alternating-current side of the synchronous converter because there is a certain fixed ratio between the alternating voltage impressed on a synchronous converter and the direct voltage delivered by it. With a single-phase converter, the alternating is 71 per cent. of the direct voltage. With a three-phase machine the alternating is 61 per cent. of the direct voltage. Hence, to change the direct voltage delivered by the converter, the alternating must be varied ac-

* See author's PRACTICAL ELECTRICITY.

cordingly. By changing the field excitation, a converter may be made to correct or compensate for low power factor. The direct e.m.f. impressed on the line by a synchronous converter may be varied by using a booster—a small generator—either



I - Plan View

FIG. 141.—Plan view of the railway, synchronous-converter sub-station.

in the alternating- or direct-current side of the machine, or by varying the alternating impressed voltage with a potential regulator or a transformer having taps.

NOTE.—Synchronous converters are somewhat more efficient than motor-generators. They find their widest application in direct-current street railway service.

221. A Motor-generator Sub-station is shown in Fig. 142,*I* and *II*. Such an outfit may be used particularly in industrial plants, where direct-current energy is required for utilization.

The high-voltage alternating three-phase line enters the station over three wires, X, Y and Z, and passes through the choke coil, C, to the high tension bus-bars 1, 2 and 3. The line vol-

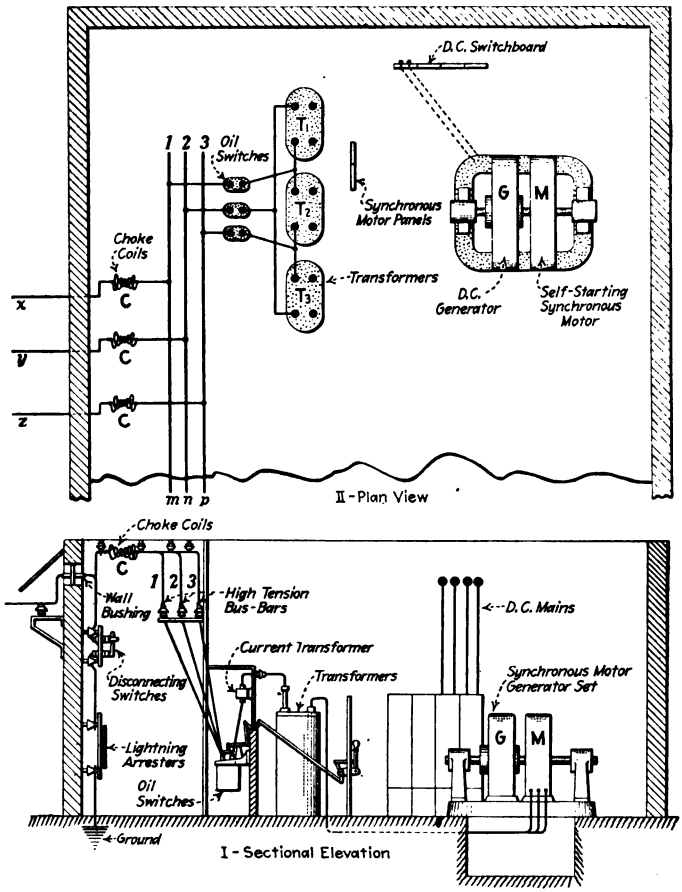


FIG. 142.—Typical arrangement of a synchronous motor-generator sub-station.

tage is stepped down to 2,200 volts by the three single-phase transformers, T_1, T_2 and T_3, which are connected in delta. The 2,200-volt alternating power drives the synchronous motor, M, which is mounted on the same shaft with and drives

the direct-current generator *G*. The synchronous motor usually has a squirrel-cage winding on its rotor and is thereby started as an induction motor.* The direct e.m.f. impressed on the line by *G* may be made any reasonable one by providing a generator of suitable characteristics, and it may be controlled manually by a field rheostat or automatically with an automatic voltage regulator. Motor-generators are sometimes preferred to synchronous converters because the motor-generators are, possibly, somewhat more readily operated. The synchronous-converter outfits are the more efficient.

222. A Frequency-changer Sub-station is one in which alternating-current power at one frequency is changed to alternating-current power at different frequency. The frequency changer sub-station is somewhat similar to the synchronous-motor sub-station of Fig. 142 except that the direct-current generator and its switching and control equipment is replaced by an alternating-current generator and outfit.* Frequency-changer stations in the United States ordinarily change from 60 to 25 cycles or the reverse.

223. Distribution Circuits may for convenience be divided into the following two general classes: (1) Series circuits (Fig. 143); and (2) parallel circuits (Figs. 144 to 148). Parallel circuits may be subdivided into: (*a*) loop circuits (Fig. 144), (*b*) tree circuits (Figs. 145 and 146), (*c*) feeder-and-main circuits (Fig. 147), and (*d*) ring circuits (Fig. 148).

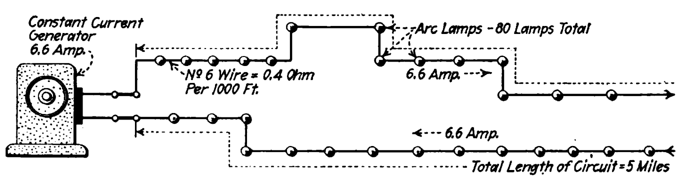


FIG. 143.—Arc-lighting circuit.

224. Series Distributing Circuits (Fig. 143) are seldom, if ever, used in this country except for constant-current‡ series arc or series incandescent lighting. The constant current in

* See the author's ELECTRICAL MACHINERY for details.
‡ See the author's PRACTICAL ELECTRICITY.

commercial series circuits is so small (usually under 8 amp.) that a small wire will carry it without excessive loss. Hence, conductors for series circuits are usually selected with reference only to their mechanical strength. It is usually considered that No. 6 wire is as small as should be erected on a pole line, hence a majority of the out-of-door series lighting circuits in this country are of No. 6 B. & S. triple-braid weather-proof copper wire. Some companies will not use any wire smaller than No. 4 B. & S. on a pole line.

225. The Line Loss in Commercial Series Circuits, using the standard No. 6 wire is relatively small as is indicated by the following example.

EXAMPLE* (see Fig. 143).—The circuit operates at 6.6 amp., is 5 miles long and serves 80 lamps, each of which requires 50 volts at its terminals. The line is of No. 6 wire which has a resistance of 2.1 ohms per mile or 10.5 ohms for the whole line. This involves a drop of ($V = I \times R$) 10.5 *ohms* $\times$ 6.6 *amp.* = 69.3 *volts*. The loss of energy in the line wire is: ($P = I^2 \times R$) = 6.6 $\times$ 6.6 $\times$ 10.5 = 468 *watts*. The power taken by one lamp ($I = E \times I$) is: 50 $\times$ 6.6 = 330 *watts* and for the 80 lamps it would be 80 $\times$ 330 = 26,400 *watts*. The loss in the line, 468 watts, is: (468 $\div$ 26,400) but 1.8 per cent. of the power taken by the arc lamps.

If No. 3 wire were substituted for No. 6, one-half the energy loss in the line wire would be saved, the cross-section and weight being twice as great, and the cost of the insulated conductor would be nearly doubled. With No. 6 wire the total weight of copper would be 2,098 lb. and the cost of the wire (insulated) would be about $500. It is doubtful if it would be wise to invest an additional $500 in order to use No. 3 wire and save one-half the energy or 238 watts, unless the cost of energy is quite high.

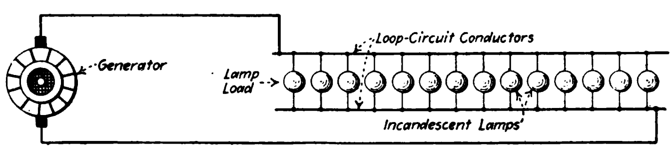


FIG. 144.—Diagrammatically illustrating a loop circuit.

226. Parallel Distributing Circuits (Figs. 144 to 148), sometimes called multiple circuits, are widely used for the distribution of electrical energy for lighting, power and heating. Com-

* Crocker's ELECTRIC LIGHTING.

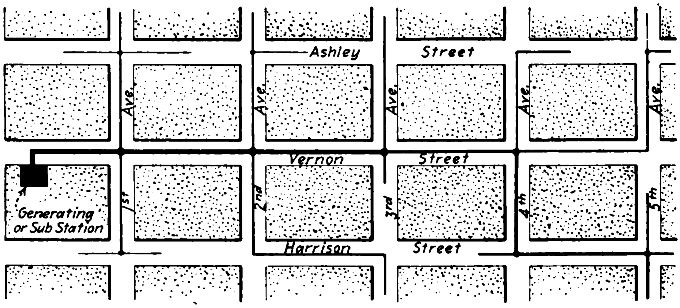


FIG. 145.—Showing a tree circuit as applied to out-of-door distribution. (This type of a circuit is called a "tree circuit" because of its resemblance to the trunk and branches of a tree.)

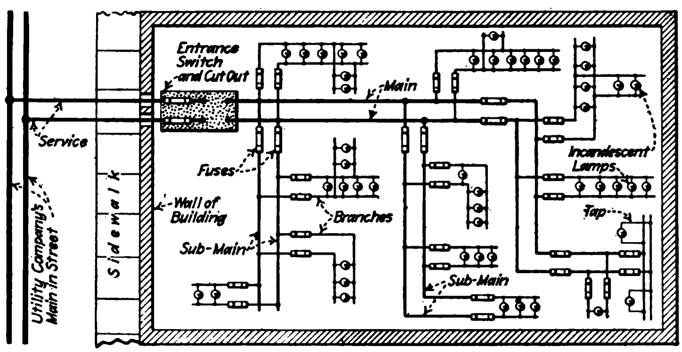


FIG. 146.—An interior distribution "tree" circuit.

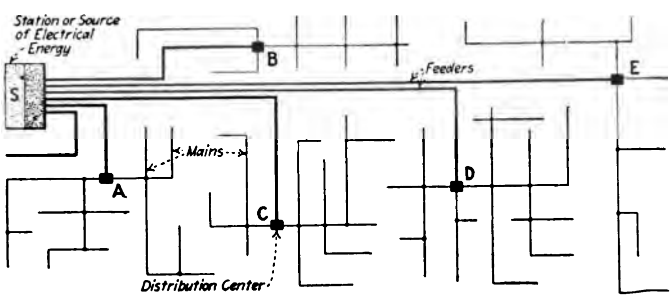


FIG. 147.—Example of a feeder and main distribution.

mercial parallel circuits are so designed that the voltage between the two sides will be approximately constant under all conditions of load. That is, sufficient copper is used to prevent the voltage drop in them from exceeding a certain small percentage of the receiver voltage which should in each case be determined by the character of the connected apparatus.

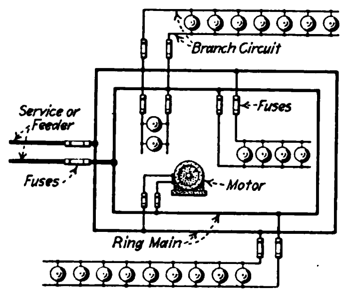


FIG. 148.—Diagrammatically illustrating a ring circuit.

Or a voltage regulator of some sort is used to maintain the voltage at the load ends of the feeders approximately constant. In dealing with parallel circuits, it is frequently assumed that the voltage, impressed on the circuit by the generator or other source of energy, is constant.

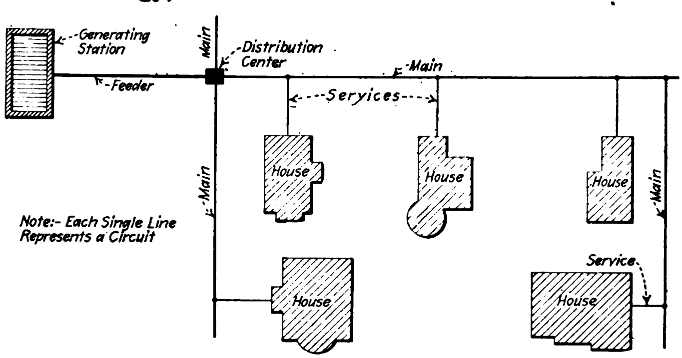


FIG. 149.—Feeders, mains and services.

227. An Important Advantage of the Feeder-and-main System (Fig. 149) is the opportunity it offers for close voltage regulation at the receivers. Receiving apparatus is not con-

nected to the feeders so the voltage regulation on them is unimportant. The regulation on the mains and services is important but they are made of wire sufficiently large that there will not be much voltage drop, even at full-load, between the distribution center, where the mains connect to the feeder, and the most distant point on the main. The voltage should be maintained practically constant at the distribution center.

228. Small Pressure Wires Are Sometimes Carried From the Distribution Center Back to the Generating or Sub-station so it is possible at any time to know exactly the voltage at the distributing center. Then the voltage at the center is maintained constant by varying the voltage impressed on the feeder at the station. Frequently the voltage at the distribution center is thus maintained constant with a potential regulator.* The varying or adjustment of voltage may be either manual or automatic.

229. In Laying Out an Out-of-door Feeder-and-main Circuit the territory to be served is subdivided into a number of districts by collecting customers in proximity to each other into groups located as near as may be at equal distances from a number of distributing centers. From these centers, the feeders are carried to the station while from the centers extend the mains, each of which serves its own groups of customers. Thus the entire territory is split up into a number of subdivisions, each in the most direct electrical connection with the central station. Each distribution center is fed by a separate and independent set of feeders.

230. In Interior Feeder-and-main Systems it is seldom feasible to regulate the voltage on the supply ends of the feeders so as to keep it constant at the center. But most of the voltage drop in the interior system can be confined to the feeders so that the voltage on the group of mains and branches served by a given feeder will be nearly the same and all of the lamps connected to them will burn at about the same brightness. Furthermore, the system is so sectionalized that the effects of trouble can be confined to small areas and that the trouble can be readily located.

* See the author's PRACTICAL ELECTRICITY.

231. A Ring Circuit, Fig. 148, is one wherein the mains form a closed ring. This is a special case of a feeder-and-main circuit. In out-of-door distributions ring mains are sometimes carried around a city block or around a certain district and branch mains or services are fed by the ring main. One feeder may serve a ring main or several may connect to it, each at a different point. In interior electrical-energy distributions, ring mains are seldom used except in industrial plants. It is sometimes expedient to carry a ring main around the interior of a shop building and connect motor taps and lighting branches to it at the most convenient points (Fig. 148). This provides a very flexible arrangement because there is then no location in the building very far away from the main, hence new motors or lights can be installed readily and economically.

SECTION 11

LIGHTNING PROTECTION APPARATUS

232. The Term Lightning Protector Is Used in Preference to Lightning Arrester in this discussion because it appears that the latter designation more accurately describes the service which the apparatus in question renders. The word "arrest," according to the dictionary, means to "stop áction of." The so-called lightning arresters do not in every case stop the action and effects of lightning nor does any manufacturer make the claim that they are infallible. They do, however, afford protection or insurance against lightning damage to electrical apparatus. The measure of protection which is afforded is determined to a considerable extent by the investment which can be made in protective apparatus to supply the protection. In this respect the cost of protection against lightning is similar to the cost of protection against fire or accident. We will, therefore, in what follows, refer to lightning protectors rather than to lightning arresters. The general term "lightning protection equipment" applies not only to lightning protectors, but also to other allied devices which serve to minimize lightning damage to electrical apparatus.

233. The Term Lightning Has a Specific Significance when used in connection with electrical apparatus protection. When thus used "lightning" implies to any sort of excessively-high-voltage disturbance in an electrical generation, transmission or distribution system.

NOTE.—Commercial lightning protectors are designed to protect only against the effects of transient abnormal voltages. They are not, as a rule, designed to protect against the effects of continued abnormally high voltages, regardless of how much such high voltages may originate.

234. Lightning May Be Divided Into Two General Classes, atmospheric lightning and internal lightning. Each of these is defined in following articles.

235. Atmospheric Lightning is that due to the equalization of a difference of potential between two oppositely electrified clouds or between a cloud and the earth. The lightning strokes or lightning flashes with which everyone is familiar are manifestations of those phenomena.

236. Atmospheric Lightning May Effect an Electrical System in Either of Two Ways—by a so-called direct stroke or by an induced stroke.

237. A Direct Stroke is one where a lightning-discharge current between a cloud and the earth selects, for a portion of its path, a part of the electrical system. Then that system is said to be "struck by a direct stroke." Lightning protectors are not, as a rule, capable of affording absolute protection against direct strokes. If the current of a direct stroke passes through a lightning protector, usually that protector is destroyed. Direct strokes ordinarily strike only aerial pole lines. An overhead ground wire strung (Fig. 150) above, or adjacent to, the pole line and connected with the earth at frequent intervals affords the most effective protection against direct strokes. Observation has indicated, that the current of a direct lightning stroke will not flow along a transmission line for a very great distance. It will usually find, through some insulation breakdown, a path to earth a relatively few feet away from the point where it "struck" the line.

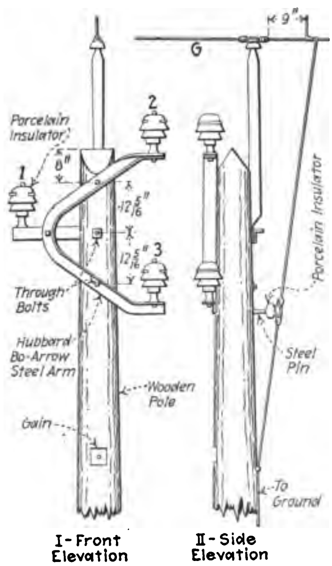


FIG. 150.—Ground wire over a three-phase transmission circuit. (The line wires take the positions 1, 2 and 3.)

238. An Induced Stroke is one whereby an abnormally high potential is developed on the electrical system, due to induction, by an atmospheric lightning discharge. Protec-

tion against the effects of induced strokes is usually satisfactorily provided by a suitable lightning protection apparatus such as will be described. The induced are much more common than the direct strokes.

239. Internal Lightning, so-called, is any abnormal voltage rise due to changes in the load on the electrical system. Examples of internal lightning are the abnormal conditions due to excessively high voltages which may occur particularly in high-voltage systems and which are caused by the opening or closing of switches or by an intermittent ground. Internal lightning effects are sometimes called *surges*.

240. A Lightning Protector Is an Electrical Safety Valve.—The duty of the protector on an electrical system is to relieve the system of abnormally high voltages, in a manner somewhat analagous to that in which a safety valve relieves a steam boiler of an excessively high pressure. Just as the safety valve should stop the escape of steam after the abnormal conditions have been relieved, so should a lightning protector stop the flow of current after the high potential has been relieved. Thus, any device which will, under the influence of a voltage above normal, permit current to flow through it and which will, when the abnormal condition ceases to exist stop the flow of that current, constitutes a lightning protector.

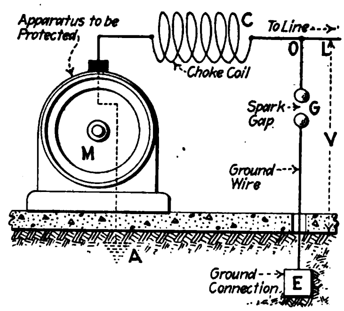


FIG. 151.—The principle of the lightning protector.

241. How a Lightning Protector Protects may be understood from a consideration of the diagram of Fig. 151. Assume that, due to some cause or other, the potential of the line L becomes much higher than that of the earth or ground. That is, assume that an abnormally high voltage, V, exists between the conductor L and the earth underneath it. Such a high voltage might originate either from atmospheric or internal lightning, as above described. The tendency of this voltage would be

to force a current from L to the earth. This current would select the path of least opposition. If there were no protection apparatus associated with the line, the path of least opposition to ground would, probably, be through the windings of the generator, M, to its frame and from thence to earth, A, as shown by the dotted lines. That is, the high voltage would break down the insulation of some of the windings of M and force a current through them to ground. This would damage the machine and might, possibly, "burn it out." Now if an air gap, G, were connected between the line wire and ground, as shown, the path LGE through the gap to ground would probably offer much less opposition, to the flow of the lightning discharge current, than would the path $LCMA$ through the generator to ground. The reason for this is that the path through the generator would probably be one of relatively high inductance, whereas the path through the air gap, G, to ground would be one of practically no inductance.

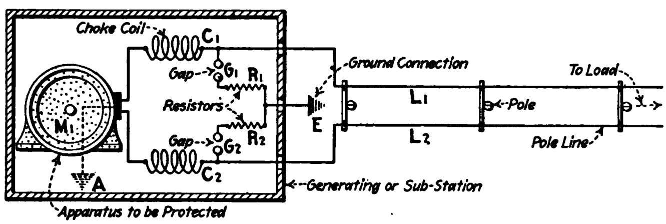


FIG. 152.—Diagram indicating typical arrangement of lightning protection equipment.

NOTE.—Lightning discharge currents are always of high frequencies or the equivalent thereof. Hence, a path containing inductance offers great opposition to their flow. It is a fact that* the electrical opposition, that is, the impedance offered by an inductive circuit to the flow of an alternating current increases as the frequency of the current increases. Therefore, the abnormal potential on L would probably be relieved by a flow of high-frequency current through G to the ground, E. The air gap, G, is long enough to prevent its break down and a flow of current under normal conditions. Fig. 152 will give a better idea of actual conditions. The resistances, R_1 and R_2, are provided to limit the current so that after the abnormal voltage condition has been relieved the generator, M_1, would not force current via the path $G_1R_1R_2G_2$. If these

* See the author's PRACTICAL ELECTRICITY.

resistances or their equivalent were not provided, the generator might continue to force current via the path shown even after the abnormal voltage condition had been relieved. The reason is that after an electric arc has been established across a gap, a relatively small voltage is sufficient to maintain it. A number of different devices which are used in practice as an equivalent for the spark gaps illustrated in Figs. 151 and 152 and some schemes utilized for preventing the flow of current after the high voltage has been relieved are described in succeeding articles.

NOTE.—Instead of there being a difference of potential between the line, L_1L_2 (Fig. 152) and the earth there might be an abnormal difference of potential or voltage (internal lightning) between L_1L_2. If the gaps G_1 and G_2, were not provided this excessive pressure might break down the insulation in M and damage it. But with the gaps, G_1 and G_2, in place, the equalization current would flow via $G_1R_1R_2G_2$ so that then the machine would not be damaged.

242. The Function of a Choke Coil, C_1C_2, Fig. 152, in lightning protection is to increase the inductance, therefore opposition, of the circuit in which it is inserted. It thereby tends to force the "high-frequency" lightning current to ground through the lightning protector. Commercial types of choke coils will be described in following paragraphs. If a surge, due to external or internal lightning, travels along a transmission line, it induces a very high voltage in any inductive winding which it encounters. Hence, unless choke coils, which are specially designed to provide this inductance, are inserted between the line and the apparatus (transformers or generators) the high voltage is likely to be induced in the turns of the apparatus and cause an insulation breakdown and consequent damage.

NOTE.—Such damage may be extremely serious if the current circulated by the generators on the system follows the path provided by the abnormal voltage. Where choke coils are inserted as shown in Figs. 151 and 152 the high voltages will be induced in the ends of the choke coils. Damage to the choke coils should not, however, occur, because the coils are specially designed to withstand these abnormal conditions.

243. An Important Distinction Between an Alternating Current and a Direct Current From a Protector Standpoint is that the alternating voltage decreases to zero twice in each cycle, whereas a direct voltage is always in the same direction. The consequence is that the arc sustained by a direct-current gen-

erator through a spark gap after the lightning discharge current has passed is more difficult to extinguish than the arc similarly sustained by an alternating-current generator. That is, it is more difficult to stop the flow of a direct current through the spark gap of a lightning protector than it is to stop the flow of alternating current. How these characteristics are recognized in the design of lightning protectors will be described. First the direct-current types, then the alternating will be treated.

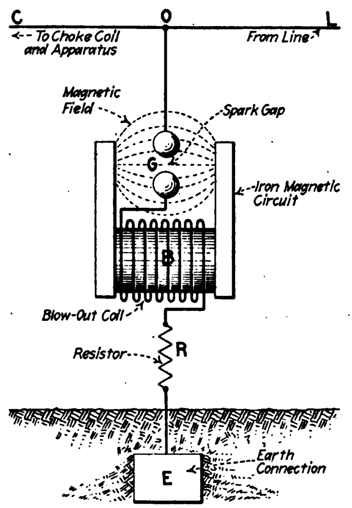


FIG. 153.—Illustrating the principle of the magnetic blow-out lightning protector.

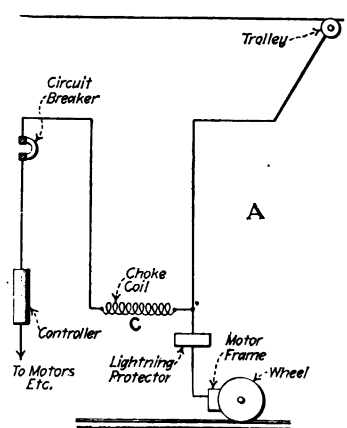


FIG. 154.—Protector on car—most desirable arrangement.

244. A Magnetic Blow-out Direct-current Protector is shown diagrammatically in Fig. 153. The spark gap, *G*, is connected in series with a blow-out coil, *B*. When the air gap, *G*, is broken down by an abnormal voltage, current flows from the line via *OGBR* to the earth, *E*. The tendency is for the current impelled by the direct-current generator to continue to flow across *G*. However, *B* develops a magnetic field as shown. An arc can not exist in a sufficiently strong magnetic field. The power-current (generator-current) arc is, there-

fore, "blown out" by the field. The resistance, R, limits the current.

245. Lightning Protectors on Electric Railway Cars may be arranged as shown in Figs. 154 and 155 to protect the apparatus on the car. Protectors should also be installed at intervals along the trolley line.* Note that choke coils, C, constitute part of the car equipment.

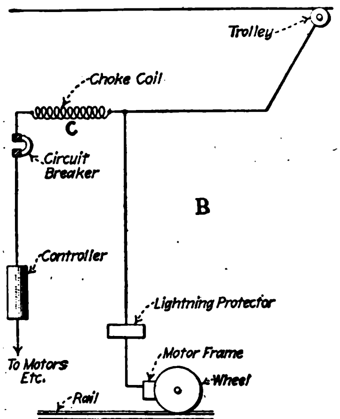


FIG. 155.

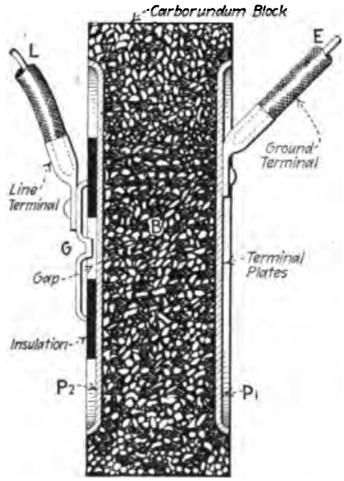


FIG. 156.

FIG. 155.—Protector on car, alternative arrangement.

FIG. 156.—Sectional diagram of the carborundum-block arrester.

(NOTE†.—The connection shown in *B* is not quite so effective as the one shown in *A*, due to the greater length of wire on the protector circuit. If it seems necessary to use the connection of *B* the arrester may be placed on the roof of the car, in the vestibule or under the car, without affecting the inductance of the circuit of the arrester. When such a connection is used, however, a larger choke coil than in *A* is necessary to offset the greater inductance of the arrester circuit).

246. A Carborundum Block Protector, which may be used on either direct or alternating-current circuits operating at pressures not exceeding 750 volts, is shown in Fig. 156. This has been designated by its manufacturer‡ as a multipath protector, because of the fact that there are many paths provided to ground for the lightning discharge current. It consists of a disc or block, B, of carborundum granules bound together with

* See the author's WIRING FOR LIGHT AND POWER.

† General Electric Company.

‡ Westinghouse Electric & Manufacturing Company.

a dielectric binding compound. On either face of the protector is mounted a metal terminal plate, P_1 and P_2. A small gap, G, is provided for line voltages of from 400 to 750. The two terminals, E and L, are connected between ground and line respectively. When under the influence of an abnormally high voltage the dielectric is broken down, the protector operates permitting current to flow. When the abnormal voltage is equalized the current flowing through the block ceases because the many minute electric arcs through the block can not be maintained by the generator pressure.

247. The Condenser-type Protector for direct-current circuits is diagrammed in Fig. 157. These are designed particularly for circuits operating at pressures of from 750 to 1,500 volts. It consists merely of a spark gap, G, in series with a resistor, R. However, the resistor is shunted by a permittor (condenser). The spark gap prevents the flow of current through the protector when the voltage is normal. When the voltage becomes abnormal current is forced across the gap and the permittor permits free discharge of the high-frequency lightning current to ground. The direct generator current can not flow because it can not pass through the permittor and the resistance of R is so great that even if G is short-circuited the direct current which will flow is negligibly small. The real function of R is to maintain the permittor in a discharged condition. Protectors of this general type but without the spark gap are also manufactured and are recommended for the protection of apparatus having weakened insulation.

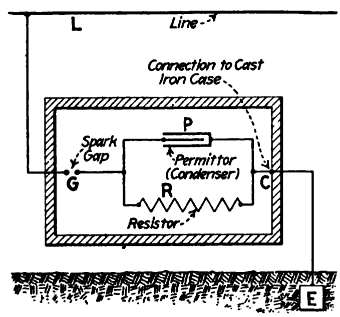


FIG. 157.—The condenser-type protector.

248. The "Circuit-breaker" Type Lightning Protector is shown diagrammatically in Fig. 158. This design comprises essentially four air gaps, G_1, G_2, G_3, and G_4, with a resistance between them. The assembled device is shown in Fig. 159.

The two gaps, G_3G_4, on the ground side of the current-limiting resistor, have connected in multiple around them a solenoid, S (Fig. 158). When a current of sufficient intensity passes through S, the iron plunger, P, is lifted by the magnetic effect thereof and then opens the circuit at B. It is due to

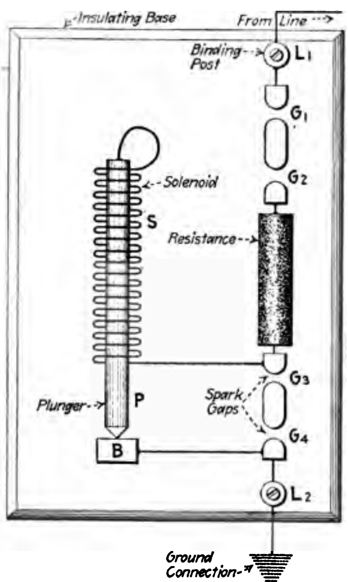


FIG. 158.—The diagram of "circuit-breaker-type" lightning protector.

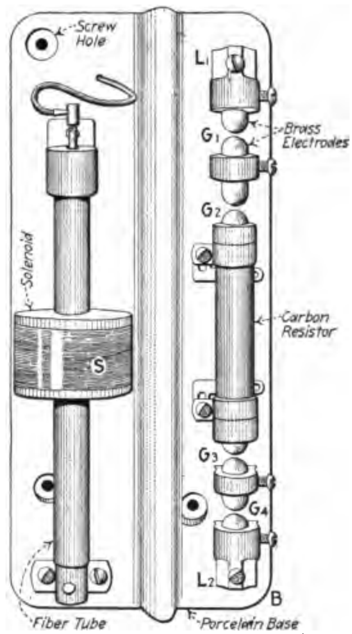


FIG. 159.—The Garton-Daniels lightning protector.

this device that the protector is called the "circuit-breaker" type. When the protector is discharging the high-frequency current of a line at abnormal voltage practically all of this current passes directly through the path $L_1G_1G_2G_3G_4L_2$ to ground. The inductance of the solenoid S is so high that practically none of the high-frequency current will go through it. However, if the power current follows the lightning discharge current through the protector, this power current will not, because of its low frequency, pass across gaps G_3G_4 but will, in

preference, take the path of lesser opposition through *S*. Thereby the plunger is raised and the arc extinguished.

249. Non-arcing Metal Cylinder Protectors (Figs. 160 and 161) may be used on alternating-current circuits operating at pressures below 300 volts. The metal cylinders are usually

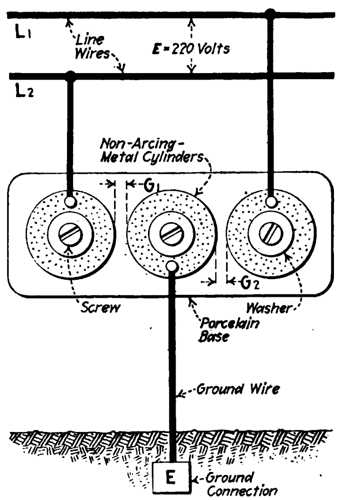


FIG. 160.—Illustrating the principle of the non-arcing metal gap protector.

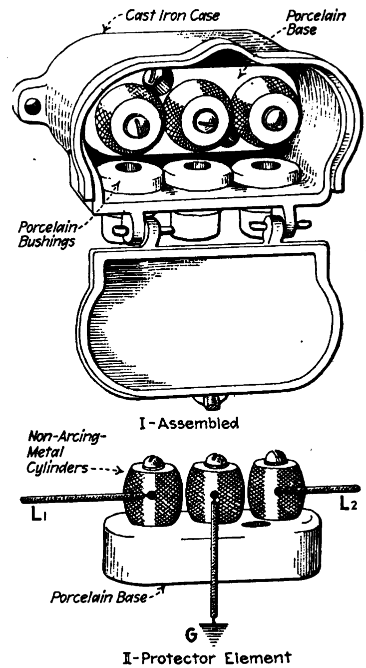


FIG. 161.—Double-pole, non-arcing metal cylinder protector.

composed of a copper-zinc alloy. In an alternating-current circuit, an arc, established by a lightning voltage, will not be maintained between these cylinders by the power current. The reason is that the arc will extinguish when the power alternating-current wave passes through zero. The zinc in the alloy vaporizes at a relatively low temperature and this vapor tends to quench the arc. There is also a rectifying phenomena in a protector of this character. The metallic

vapor conducts the current in one direction only. Therefore, when the current reverses, the metallic vapors tend to cool below the arcing temperature before the alternating-current wave is completed. Thereby, the arc may be extinguished.

250. Protectors Comprising Non-arcing Metal Caps with a Resistance in Series may be used for alternating-current circuits operating at pressures below 3,000 volts. A protector of this type (Fig. 162) comprises a sufficient number of spark gaps to prevent the passage of current at normal voltage. In series with the gaps is arranged a resistor to limit the dynamic (generator) current which tends to flow to

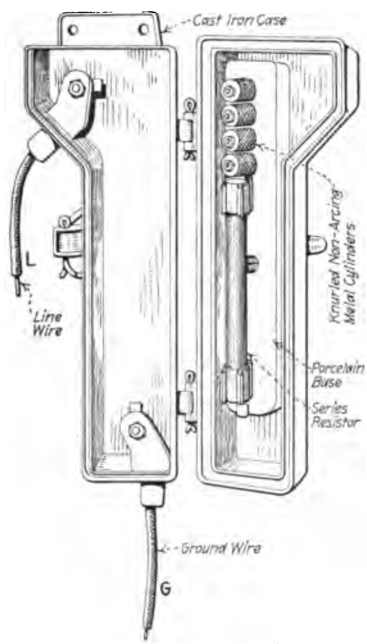


FIG. 162.—Multigap alternating-current arrester with series resistance arranged for pole mounting.

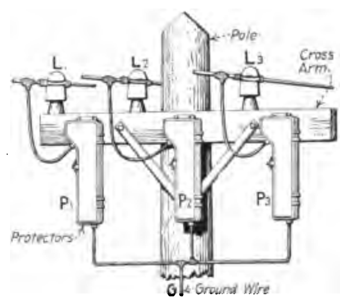


FIG. 163.—Multigap protectors mounted on a pole for transformer protection.

ground after an arc has been established through the gaps by a lightning discharge. Fig. 163 shows how three protectors, P_1, P_2 and P_3, of this type may be mounted on a pole for transformer protection. L_1, L_2 and L_3 are the line wires.

251. The Graded-shunt Resistance Protector, the principle of which is illustrated in Fig. 164, consists of a series of spark gaps (G_1 to G_{14}) associated with resistors which are shunted around them. Protectors of this general type are manufactured for voltages of from 1,200 to 13,000. That shown in

Fig. 164 is for 2,200 volts. There are three alternate paths for discharge through the protector of Fig. 164. One path comprises all of the gaps, G_1 to G_{14}, in series. Another path comprises four gaps (G_1 to G_4) in series with a relatively low resistance R_1. The other path comprises two gaps, G_1 and G_2, in series with a high resistance R_2. Three paths to ground, each of a different impedance, are thus offered through the protector. Thereby a discharge of any frequency will find a

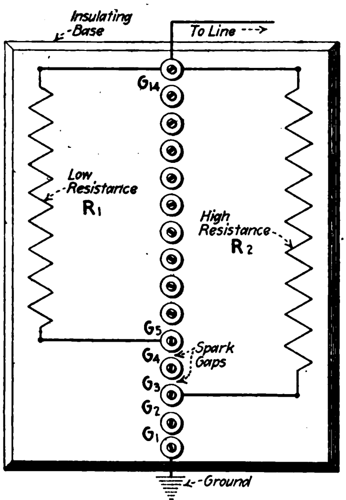


FIG. 164.—Diagram of a so-called "multipath" lightning arrester.

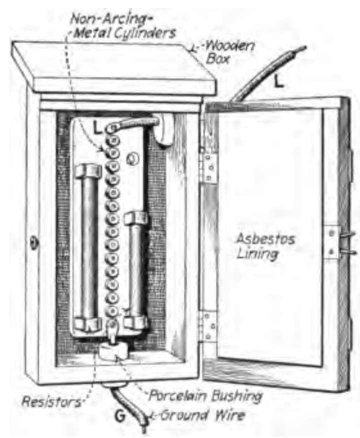


FIG. 165.—Multipath protector in wooden box for outdoor installation.

path of a relatively low impedance for it to ground. The path comprising the high resistance and the two series gaps is for discharges of low frequency or for discharging gradual accumulation of static electricity. Discharges of medium frequencies will select the path comprising the low resistance and the four series gaps. Discharges of high frequency will select the third path which includes only the gaps in series.

NOTE.—Why the lightning takes different paths may be explained thus:* When the gaps of a protector are shunted by a low resistance a discharge of the high frequencies finds it relatively difficult to pass through the resistance rods. This is because of the impedance of the

* General Electric Company.

rods. However, such a discharge will follow with relative ease across all of the gaps because of the permittive (electrostatic capacity) effect of the gaps. The series of gaps is, in effect, a number of permittors (condensers) in series. The higher the frequency the more pronounced is this effect. Hence, the discharges select the paths through the gaps and resistances which offer the least opposition. Which path is selected in any case will be determined by the frequency of the lightning discharge. By frequency is meant not the generator frequency but the equivalent lightning frequency which may be hundreds of thousands, or even millions, of cycles per second. If the power current tends to follow a lightning discharge it will, because of its relatively low frequency, select one of the paths through a resistance which will limit it. Due to the rectifying effect (described above) of the spark-gap cylinders, the arc should be extinguished at the end of the first ½ cycle after the generator current has started to flow. Fig. 165 shows one of these protectors arranged in a wooden box for outdoor work installation. *G* is the ground wire and *L* is the line wire.

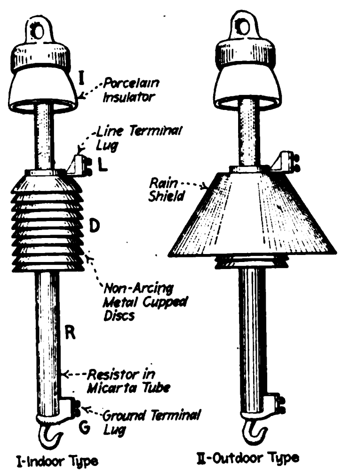


FIG. 166.—The "cupped-disc-gap" protector. (Westinghouse Elec. Mfg. Company.)

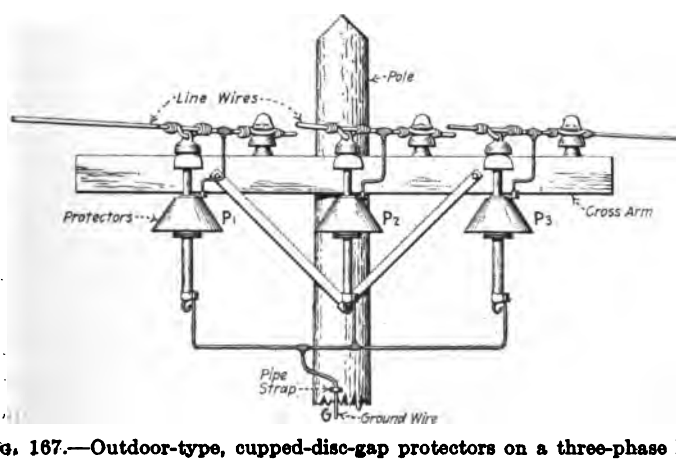


FIG. 167.—Outdoor-type, cupped-disc-gap protectors on a three-phase line.

252. A Cupped-disc Gap Protector is delineated in Figs. 166 and 167. This type of equipment may be designed for alternating-current pressures of from 3,000 to 13,000 volts. It comprises (Fig. 166) a series of cup-shaped discs, D, of a non-arcing metal supported on an insulating rod, together with a resistance, R, in series. The line wire is connected to terminal, L, and the ground wire to G. This form was designed specially for distributing-transformer protection and in practice is arranged on the pole line as shown in Fig. 167 by suspending it from the line wire with a porcelain insulator. P_1, P_2 and P_3 are the protectors.

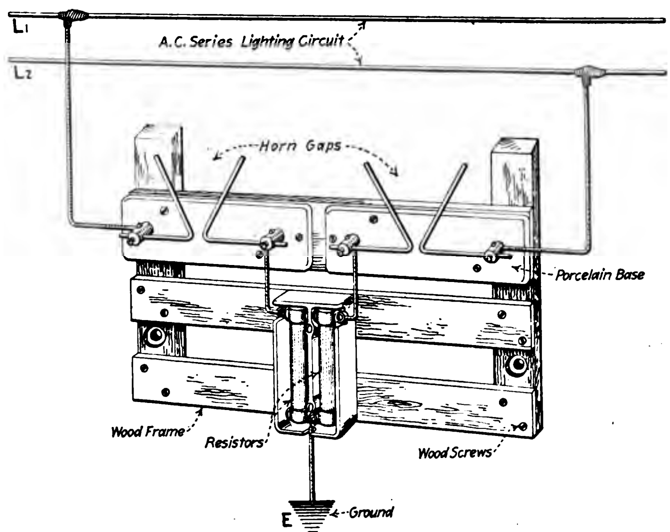


FIG. 168.—Horn-gap protector for A. C. series lightning circuits.

253. Horn-gap Protectors are shown in Figs. 168 and 169. An electric arc once established, due to some cause or other, between two horns tends to extinguish itself. The arc rises on the horns, due to the upward flow of the column of hot gases and finally attains a length of gap which it cannot maintain. Fig. 168 shows a protector of this type for use on alternating-current series street lighting circuits where the normal pressure does not exceed 1,500 volts. L_1 and L_2 are the line

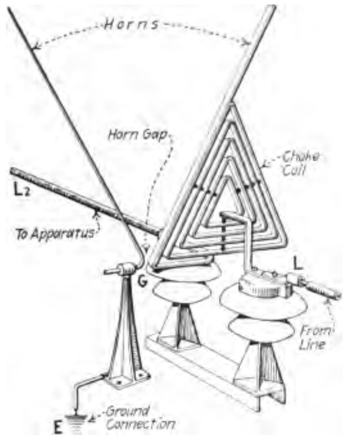


FIG. 169.—Horn-gap, choke-coil protector for alternating-current lines.

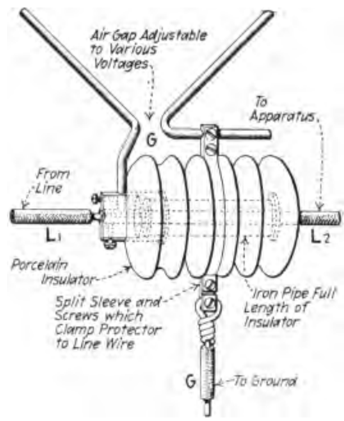


FIG. 170.—The Pierce line-wire, horn-gap protector. (The iron pipe acts as a choke coil.)

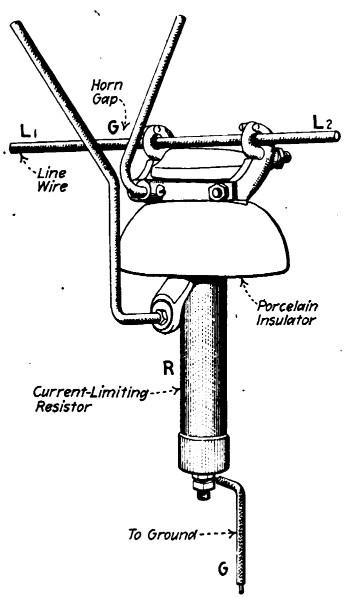


FIG. 171.—The Burke suspension lightning protector for pressures up to 6600 volts.

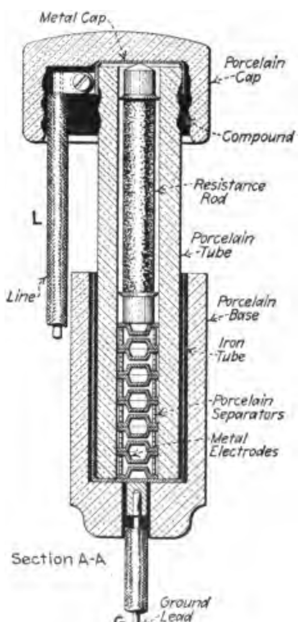


FIG. 172.—The General Electric Company compression-type lightning protector.

wires and E is the ground connection. Protectors of this same general form are manufactured for alternating pressures up to 9,000 volts. Abnormal voltage conditions, due to surges, are common on alternating-current series lighting circuits. Such surges may be caused by the opening, short-circuiting or grounding of the circuits. These simple horn-gap protectors appear, for this service, to provide effective protection. Electrolytic protectors, the principle of which will be described later, are preferable for the protection of direct-current series lighting circuits. Figs. 170 and 171 show recently developed types of horn-gap protectors arranged for suspending on line wires. In both of these illustrations: L_1 is the line-wire connection; L_2 leads to the apparatus (or choke coil if there is such); and G is the ground wire. A current-limiting resistor R is provided in the protector of Fig. 171.

254. A Combination Choke Coil and Horn-gap Protector is shown in Fig. 169. These protectors are designed for alternating-current voltages of 33,000 and above. If an arc is established across the gap G it tends to rise and extinguish itself as above described. And, furthermore, the choke coil produces a magnetic field which, because of the phenomena described above in connection with a magnetic blowout protector, assist in the rapid quenching of the arc.

255. The Compression-type Protector (Fig. 172) comprises a number of gaps arranged in series with a resistor inside of a closed porcelain tube. An iron tube which is grounded, surrounds the air gaps and equalizes the electrostatic gradient. When a discharge passes between the metal electrodes which form the gaps, it expands the air and compresses it, thus extinguishing the arc. Protectors of this type are most frequently used on 2,200-volt pole lines for distributing-transformer protection. They have a limited discharge capacity.

256. The Electrolytic Lightning Protector, provides, probably, the most effective insurance against lightning damage now known. Protectors of this type can be furnished for alternating-current and direct-current circuits of any commercial voltage. Their disadvantages are that they are relatively expensive and that they require a certain amount

of attention. However, these disadvantages are of minor consequence when expensive equipment is to be protected. Only the alternating-current protectors will be described here.

257. The Principle of the Electrolytic Protector may be understood from a consideration of Figs. 173 and 174. The protector consists of a stack (Fig. 173) of cone-shaped, aluminum plates or trays spaced about 0.3 in. apart. A solution of electrolyte is poured into the spaces between the plates. The completed stack is mounted in an iron tank which is then filled with oil. The oil not only prevents the evaporation of the electrolyte but also prevents a rapid rise in temperature when the protector is discharging. The upper plate of the stack is connected to a horn gap (Fig. 175). The lower plate is also usually grounded on the tank which is also (on a grounded neutral system) connected to ground.

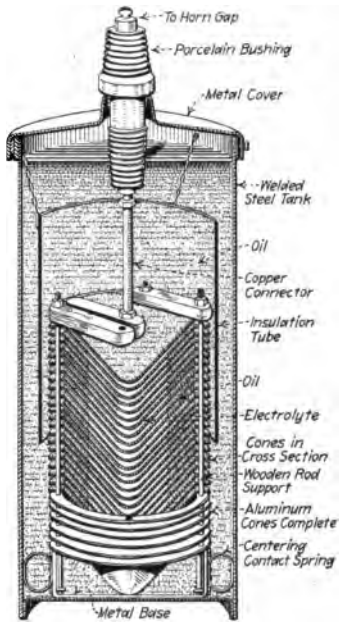


FIG. 173.—Sectional elevation of a General Electric Company electrolytic protector.

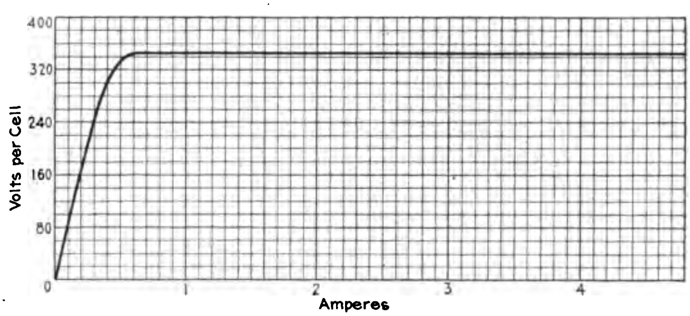


FIG. 174.—Graph showing how the electrolytic protector permits current to flow readily at pressures above 330 volts per cell.

258. The Chemical Action of the Electrolyte usually is such that it forms on the surfaces of the aluminum plates a film of hydroxide of aluminum. At voltages below about 350 (Fig. 174) this film has an exceedingly high resistance. However, at voltages in excess of 350 the resistance of the film is very small. Thus, an electrolytic cell arranged as suggested, forms an electrical safety valve which operates at a pressure of approximately 350 volts. However, at voltages below 350 some current would flow through the protector if it were left connected to a "line" circuit wire. Therefore, it is

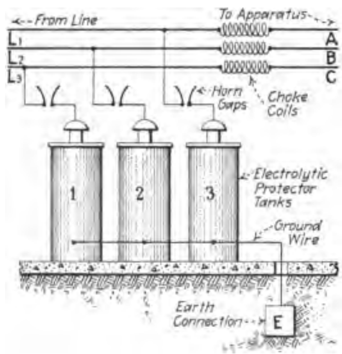


FIG. 175.—Schematic connection diagram for a grounded-neutral, three-phase electrolytic protector.

necessary to connect in series with it a horn gap, as shown in Fig. 175. The number of aluminum plates which is necessary to connect it in series is determined by the normal voltage of the line to be protected. There should be one cell, approximately, for each 350 volts of normal line pressure. Fig. 176 shows the construction of an electrolytic protector for 150,000 volts. Fig. 177 shows a complete installation.

NOTE.—For charging an electrolytic protector the horn gaps are closed together by moving a suitably arranged lever. One side of the horn gap is hinged to provide for this.

259. The Arrangement of Electrolytic Protectors on Grounded and Ungrounded Neutral Three-phase Systems is shown respectively in Figs. 175 and 178. Where the neutral

is grounded, a voltage greater than the normal voltage between phase wires (L_1, L_2 and L_3) can never be impressed across any one of the three cells (1, 2, and 3) if they are arranged as

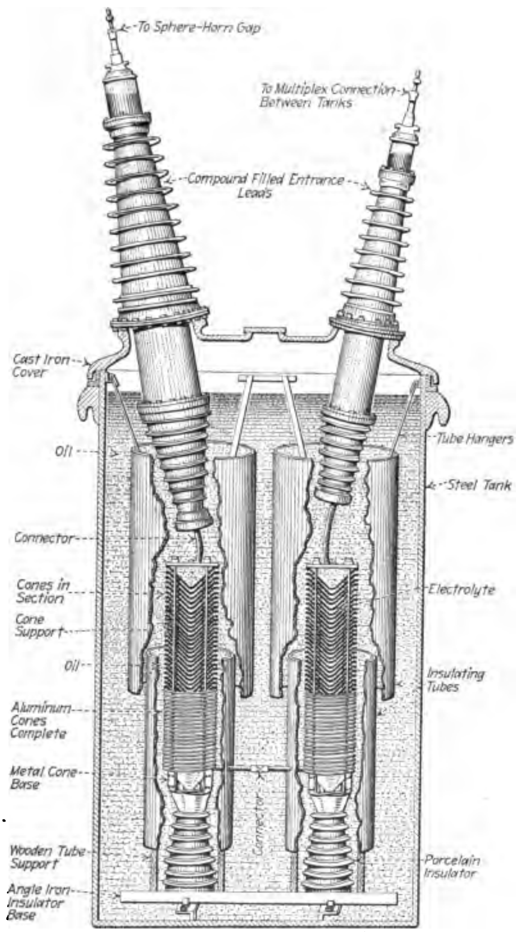


FIG. 176.—Section through a general-electric-company 115,000–135,000-volt electrolytic arrester tank.

shown in Fig. 175. However, if the neutral is ungrounded and an accidental ground occurs some place on the line, a voltage equal to almost twice normal voltage (1.73 × normal

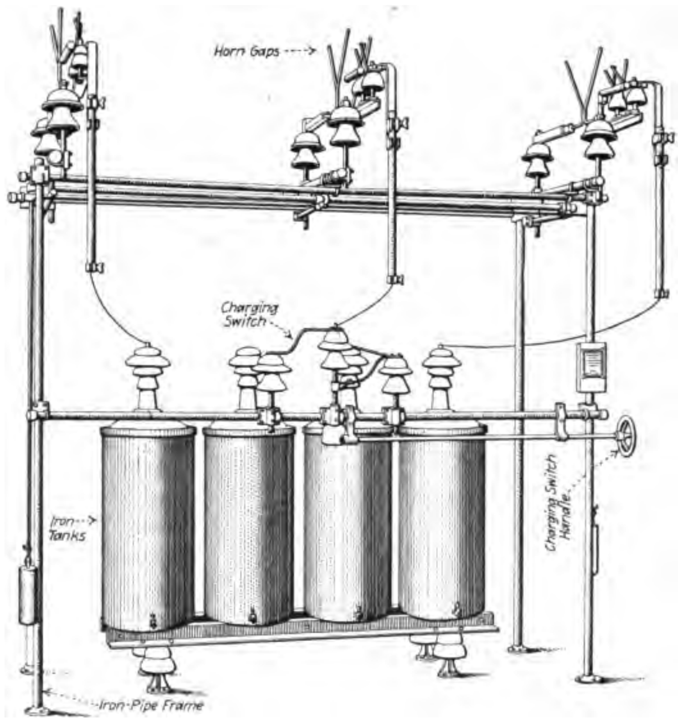


FIG. 177.—A Westinghouse Electrolytic protector for a three-phase, ungrounded neutral 22,000-volt circuit.

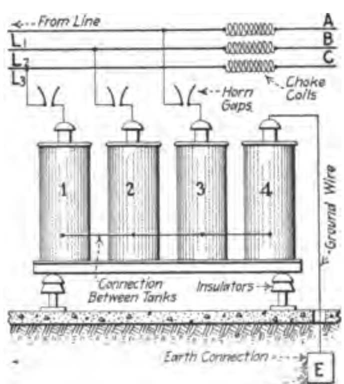


FIG. 178.—Schematic diagram for an ungrounded neutral three-phase electrolytic protector.

voltage) would be impressed across one of the protector tanks if only three were used (Fig. 175). Therefore, where the neutral is ungrounded, a fourth cell or tank (4) is placed in the ground lead, as diagrammed in Fig. 178, to insure that a voltage greater than normal will never be impressed across any one of the four cells. E is the ground connection.

260. In Selecting Choke Coils it is necessary to exercise judgment. In a general way the protective ability of a choke coil increases as the square of the mean diameter of the coil. With choke coils of equal length and equal mean diameter* the protective ability varies as the square of the number of turns. From the standpoint of lightning protection a large choke coil is desirable. However, the larger the coil the greater its impedance and resistance. If a coil is too large the voltage drop and energy loss in it will be excessive, hence in selecting the coil it is desirable to consider these features and choose one of a size which practice has shown to provide sufficient protection without excessive energy loss or voltage drop.

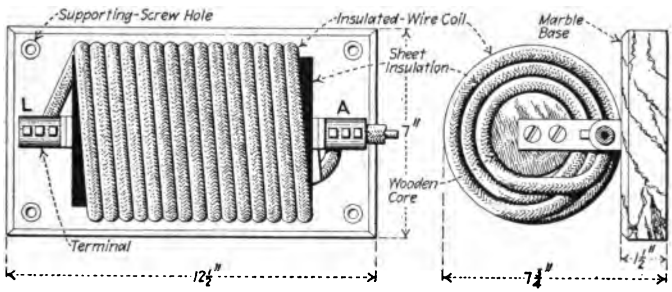


FIG. 179.—100-amp. choke coil designed for pressures of 6600 volts and lower (General Electric Company.)

261. A Choke Coil for Low-voltage Circuits is shown in Fig. 179. It comprises merely a coil of insulated wire of sufficient cross-sectional area to carry the current of the circuit into which it is to be connected. This coil is wound on an insulating core which is mounted on an insulating base.

* Westinghouse Electric and Manufacturing Company.

Suitable terminals are provided. The core is not necessary except to insure mechanical rigidity. Home-made choke coils can be readily constructed by forming a helix of wire.

262. Air-insulated Choke Coils for higher voltages are constructed as suggested in Figs. 180, 181 and 182. The type shown in Fig. 180 offers very effective protection, but is ex-

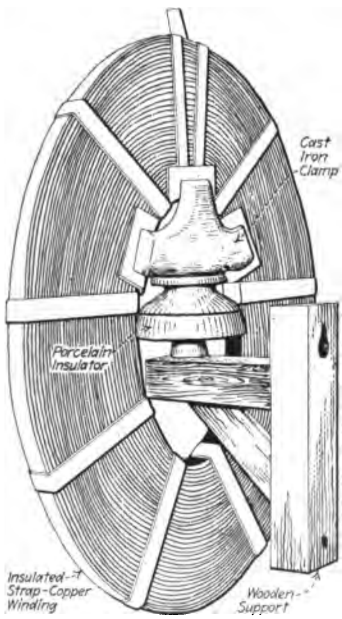


FIG. 180.—Westinghouse "pancake type" Choke coil for pressures of from 2200 to 25,000 volts.

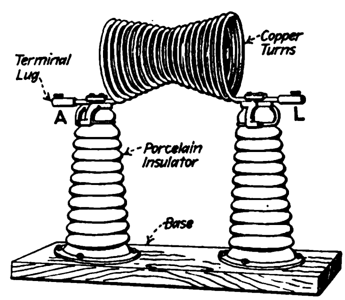


FIG. 181.—General Electric Company "hour-glass" choke coil insulated for 35,000 volts.

pensive because of the large amount of copper involved in its construction. Hence, coils of the general design of Figs. 181 and 182 (*A* is the apparatus terminal and *L* the line terminal) are used more frequently, particularly on very high-voltage lines for which the construction of Fig. 180 would not be suitable.

263. Oil-insulated Choke Coils are sometimes used on high-voltage alternating-current lines and comprise merely (Fig. 183) a coil immersed in a suitably-insulated and designed

steel tank which is filled with oil. The oil insulates the coil against side flashes and dissipates the heat developed in it so that a conductor of small cross-sectional area can be used for the coil.

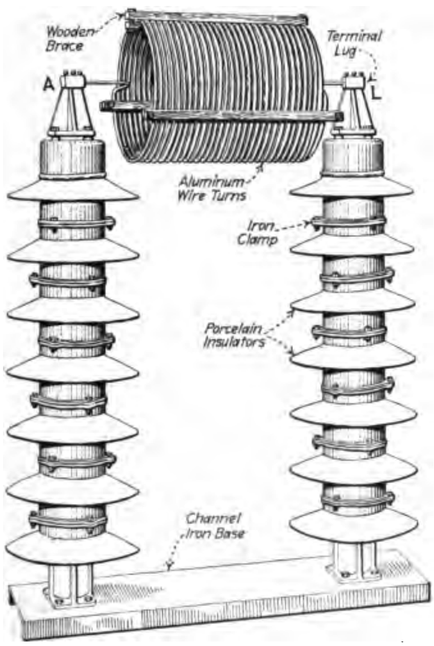


FIG. 182.—Air-insulated choke coil for pressures up to 150,000 volts.

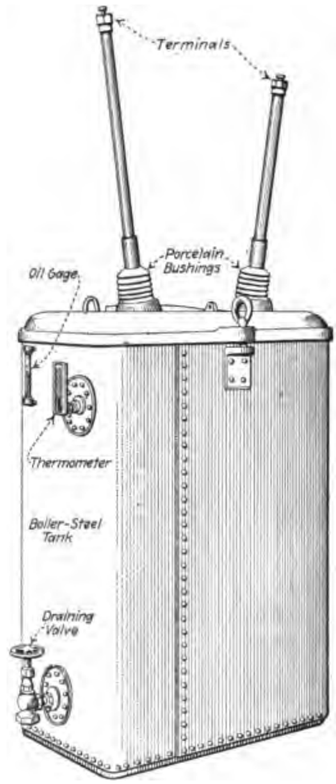


FIG. 183.—Westinghouse oil-insulated, self-cooling choke coil for pressures of from 25,000 to 70,000 volts.

264. Application of Alternating-current Lightning Protectors.—The following table indicates in a general way the services for which certain of the Westinghouse protectors of the different types are fitted. The price increases from the top to the bottom of the table.

General class	Type	Max. volts	Station capacity	Usual application	Remarks
Carborundum block	MP	400 750	Unlimited	Outdoors on line for protection of low-voltage motor installations	A low-priced arrester giving good protection on low-voltage circuits.
Non-arcing-metal cylinder	C	1,250 2,500	200 kw. (or higher if more than 2 miles from station)	Outdoors on line and for transformer protection	Maximum protection (within limits of station capacity) possible in low-priced arresters.
Non-arcing-metal cylinder with series resistance (single-pole)	CR	2,500	Unlimited	Same as type C	Similar to type C but with resistance; for use at higher station capacities. Single-pole only.
Non-arcing-metal cylinder with series resistance (double-pole)	G	2,500	Unlimited	Same as type C	Similar to type CR except multipole
Cupped-disc gap	W	6,600 13,200	Unlimited	Outdoors for transformer protection	Similar to type CR but for higher voltages.
Graded-shunt resistance	S	3,500 7,000 11,000 13,200	2,000 kw.	Indoors for apparatus. Outdoors for transformers	Greater protection than foregoing. A low equivalent arrester suitable for small stations or extra good protection of transformers.
Graded-shunt resistance	L.E.	2,000 to 39,000	Unlimited	Same as type S	Same as type S except for larger stations and higher voltages.
Electrolytic or aluminum cell	AK	2,000 to 145,500	Unlimited	Same as types S and L. E.	Maximum protection possible in present state of the art. Should be used in all cases of high voltage and at all voltages where conditions are severe or importance of protection is considered above cost.

SECTION 12

AUTOMATIC VOLTAGE REGULATORS

265. The Desirability of Maintaining Constant the Voltage Impressed by a Generator is well recognized. This is particularly true where an incandescent lamp load is served by the generator. The graph of Fig. 184 shows that a small decrease in voltage results in a material decrease of candle-power and wattage. A decrease in the wattage involves a corresponding loss in revenue to the central station. A decrease in candle-power involves dissatisfaction of the consumer.

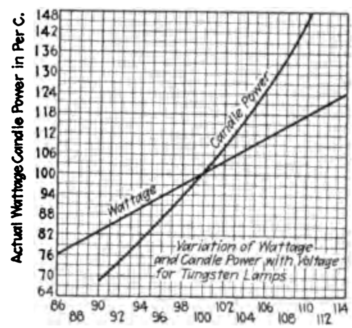


Fig. 184.—Graph showing variation of candle power and wattage of tungsten lamps with variation in impressed voltage.

Example.—Referring to the graph of Fig. 184, a 2 per cent. decrease in voltage decreases the candle-power to 93½ per cent. of the normal candle-power and the wattage to 96½ per cent. of the normal. Furthermore, fewer lamp renewals are necessary where the voltage impressed on the lamps is maintained constant and also higher-efficiency lamps may be used. When the voltage increases above normal, the lives of the lamps are correspondingly decreased. While for the operation of motors it is not so essential that the voltage variation be a minimum, it is desirable because burn-outs of motors and control apparatus may result if the voltage is too low.

266. There are Several Factors Which Tend to Cause Variations in the Voltage impressed by the generator on the bus-bars. The prime-mover speed may not be constant—this holds true for both steam prime movers and waterwheels. Voltage variation can also be due to the $I \times R$ drop in a gen-

erator which increases with the load. With alternating-current machines, variation in generator voltage will result when the exciter voltage varies due to some cause or other.

267. The Function of the Automatic Voltage Regulator is to maintain constant the voltage which is impressed by a generator on the bus-bars. This function is performed accurately and most satisfactorily by automatic regulators of the Tirrill type, the principles of which will be described in following articles.

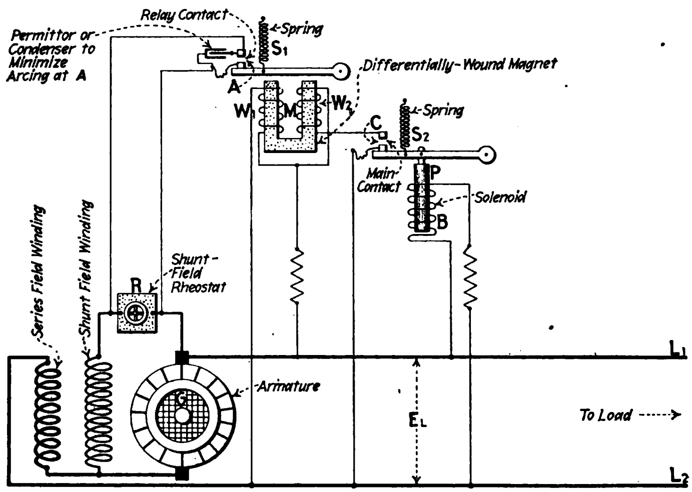


FIG. 185.—Arrangement of an automatic voltage regulator for a small direct-current generator.

268. The Principle of the Automatic Voltage Regulator is illustrated in Fig. 185. The voltage impressed by any generator on its bus-bars can be maintained almost constant by a man operating the field rheostat. However, such a method would be very expensive and would not effect as close voltage regulation as will the automatic device to be described. The principle of the automatic regulator is this: If the voltage impressed by the generators on the bus-bars increases, the automatic regulator places a shunt circuit around (or short-circuits) the field rheostat of the machine. This permits a greater field current to flow and the generator voltage then

increases. When the generator voltage has attained normal the short-circuit around the field rheostat is removed and the voltage then tends to decrease. In an actual regulator controlling a generator serving a varying load, this short-circuit is continually being placed around the rheostat or moved therefrom, as occasion demands. The result is that the contacts which make and break the short-circuit path are moving continually somewhat as the contacts in an electric vibrating bell move. However, the vibration of the automatic regulator contact is not uniform because under certain constant load conditions, the contactor may not vibrate at all. Obviously, then, the regulation depends on the rapid making and breaking of the short-circuit in contacts.

EXPLANATION.—The arrangement of Fig. 185, showing a voltage regulator for a small direct-current generator, is designed to maintain a constant voltage, E_L, across bus-bars L_1L_2. The closing of the contact A short-circuits the field rheostat, R. The opening and closing of contact A is in turn controlled by the differential magnet M. Magnet M has two opposing windings, W_1 and W_2. One of these windings is in series with contact C, the opening and closing of which is controlled by relay B which is connected across the bus-bars. When C is opened only winding W_1 is excited. A is then opened by the pull of W_1. When contact C is closed, W_2 is also excited, which neutralizes the effect of W_1. Then A is closed by the action of the spring S_1. Now, if the voltage, E_L, rises above normal, relay B is excited sufficiently to overcome the pull of spring S_2. B then pulls down plunger P and opens contact C, deënergizing W_2. Thereby contact A is opened, removing the short-circuit path around R and inserting R in the shunt-field circuit. The insertion of R in the field circuit decreases the field current and excitation and decreases the voltage developed by G. If the voltage, E_1, decreases, the operation is reversed. The ultimate result is that the contacts A and C are in almost constant vibration. They remain either open or closed for such longer or shorter intervals as may be necessary to maintain E_L constant.

269. Voltage Regulators for Small Direct-current Generators operate on the same principle illustrated in Fig. 185 and described in the above explanation. The exterior appearance of one of these devices is shown in Fig. 186, which is lettered to correspond with the diagram of Fig. 185. If the shunt-field current is greater than can be satisfactorily ruptured by one contact, A (Figs. 185 and 186), several of these contacts can

be arranged in multiple. A multiple-contact regulator, operating on the principle shown in Fig. 185, can control direct-current generators of capacities up to 125 kw.

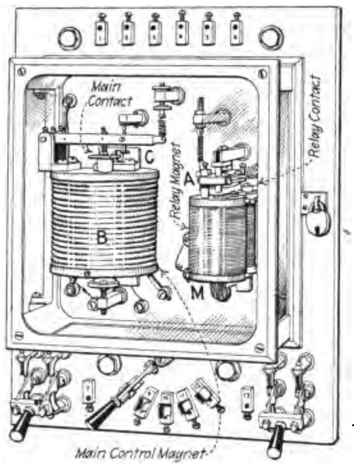


FIG. 186.—Regulator for small direct-current generators.

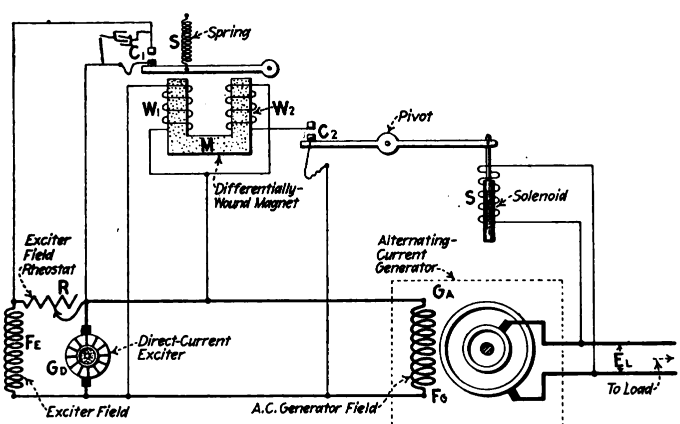


FIG. 187.—Illustrating the principle of an automatic voltage regulator as applied to a small alternating-current generator.

270. The Principle of the Alternating-current Regulator is shown in Fig. 187. This operates on the shunt-field circuit of the exciter, thereby controlling the alternating-current gen-

erator field. Fig. 187 shows only the principle, because, as will be described, the actual construction of the regulator for an alternating-current circuit is more complicated than that suggested in Fig. 187.

EXPLANATION.—If the alternating-current generator voltage, E_L (Fig. 187), increases above normal the plunger in the solenoid or relay S is raised. This opens contact C_2. Then winding W_2 is deënergized and the pull of W_1 opens contact C_1, thereby the resistance, R, is inserted in the exciter-field circuit. The voltage E_L will decrease, which weakens the pull of S, closing contact C_2. Then, because the effect of W_2 neutralizes that of W_1, spring S will close C_1. Thereby R is short-circuited and the exciter-field excitation of G_D is increased. Thus, the alternating-current generator voltage is again raised.

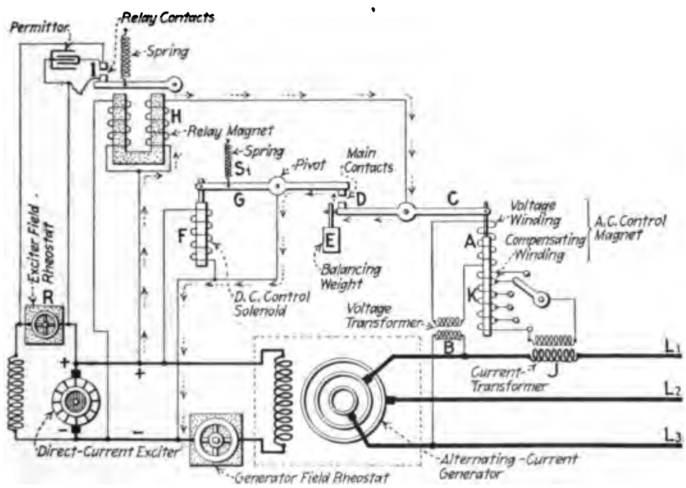


FIG. 188.—Automatic voltage regulator for large alternating-current generators. (This shows a three-phase generator.)

271. The Actual Arrangement of Voltage Regulators for Alternators is diagrammed in Fig. 188 and their appearance shown in Figs. 189 and 190. Greater sensitiveness of control is effected with this device than with those of Figs. 185 and 187. Solenoid A is energized by a current proportional to the voltage on the bus-bars. It is usually fed through a potential transformer, B. The core of A is attached to a lever C. On the opposite end of C is a contact D and a balancing weight E.

When A is energized C is lifted and D is opened. The windings A and K (the function of K will be described later) constitute the alternating-current control magnet. The direct-current control magnet F is connected across the exciter terminals.

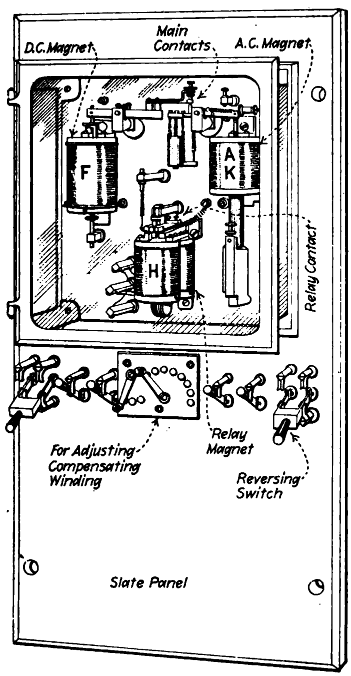


FIG. 189.—Automatic voltage regulator for small capacity exciters mounted on a 31-in. panel for insertion in a switchboard.

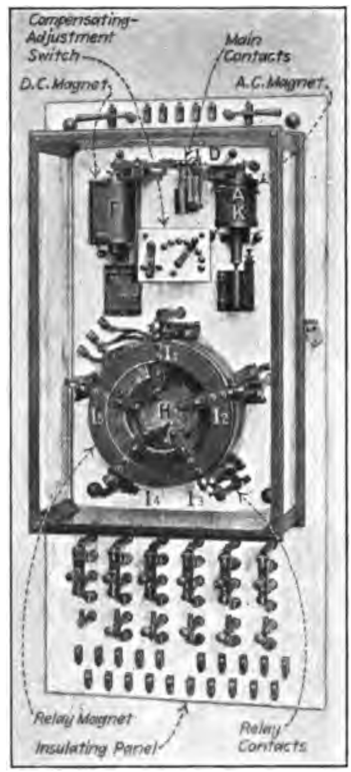


FIG. 190.—A large capacity regulator having five relay contacts. (See Figs. 188 and 191 for diagram).

When F is energized G is pulled down against the tension of the spring S_1, tending to open the contact D. The pull on F is in direct proportion to the exciter voltage. All other features are substantially similar to those previously described.

EXPLANATION.—If the alternating voltage decreases to below normal, the plunger in *A* (Fig. 188) closes contact *D*. This permits current to flow via the path shown by the dotted arrows, thus closing contact *I* and short-circuiting the exciter-field rheostat. Thereby the exciter voltage and the alternating voltage is raised. Now as the exciter voltage increases, *F* is energized and contact *D* is raised. However, if the alternating voltage remains low the lower contact at *D* follows the upper one. If now the alternating voltage increases above normal contact *D* is opened, which again causes *R* to be inserted in the exciter-field circuit. Where

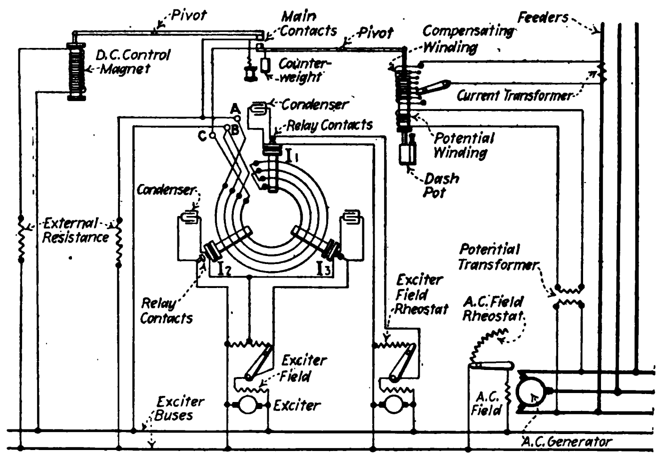


FIG. 191.—Schematic diagram of connections for a regulator controlling large exciters, several relay contacts are used.

the exciter capacity is small or where there is only a single exciter one contact suffices (Fig. 189) at *I*. In stations where there are a number of exciters the relay *H* operates a number of contacts, *I*. There may be one or more than one relay contact for each exciter as shown in Figs. 190 and 191. In important installations a separate regulator may be used for each exciter.

272. A Voltage Regulator for Large Direct-current Generators operates on a principle similar to that diagrammed in Fig. 188. However, in the direct-current regulator, the contacts must short-circuit the generator-field winding because there is no exciter on which they can act.

273. The Capacity of the Relay Contacts, in amperes, is what, in general, determines the capacity of the regulator. One contact has a capacity of about 50 kw. of exciter output,

which is equivalent to, approximately, a 2,000-kw. alternating-current-generator output. Where the capacity of the exciter

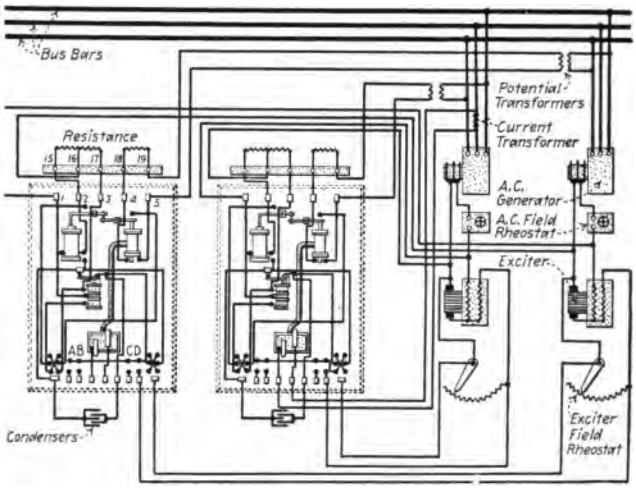


FIG. 192.—Connections of small-capacity regulators with one arrangement of two exciters in parallel.

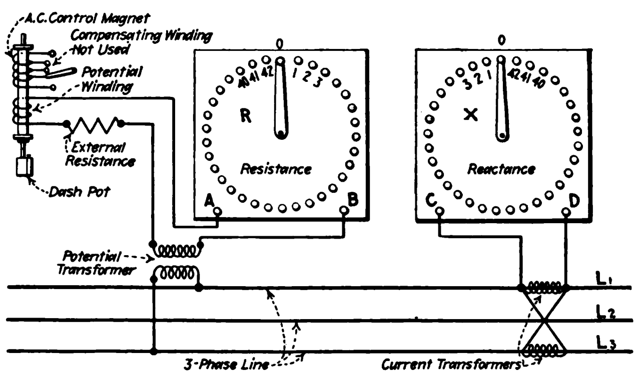


FIG. 193.—Arrangement of a line-drop compensator for a voltage regulator.

is in excess of about 50 kw., additional contacts must be arranged in series, each shunting a portion of the exciter-field rheostat.

274. The Operation of Generator Voltage Regulators in

Parallel is the practice in many important installations in which each generator has an individual exciter and regulator, the combination comprising a complete and distinct unit. Fig. 192 illustrates an arrangement of this type. Cross-currents between the generators, which might occur because of the exciters having different characteristics, are eliminated by a certain arrangement of voltage and current transformers.

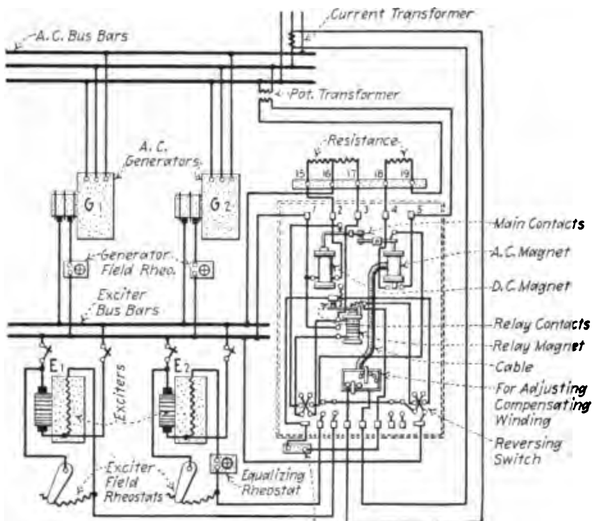


FIG. 194.—Arrangement of an automatic regulator for exciters of small capacities controlling several alternating-current generators in parallel with their exciters in parallel.

275. Compensation for Line Drop is effected by means of a compensating winding (K, Fig. 188). The object of this compensation is to maintain, as nearly as practicable, a constant voltage at a center of distribution out on the line distant from the generator and station. As the current through L_1 (Fig. 188) increases the excitation of K increases accordingly. The pull of K being proportional to the line current is, in general, proportional to the line drop. Therefore, the pull of K, in combination with that of A, can be so proportioned that the average line drop will be compensated for by the regulator.

A dial switch is provided in combination with K to provide the proper value of compensation for the feeder circuit in which current transformer J is inserted. A special compensator (Fig. 193) is provided where it is necessary to compensate for both resistive and inductive drop.

276. Connections for Voltage Regulators for Different Services are shown in Figs. 192 and 194. There are almost innumerable possibilities in the arrangement of these regulators for different services. Those illustrated are typical.

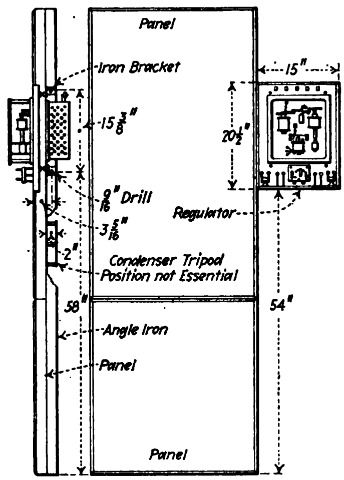


FIG. 195.—Regulator mounted at side of a switchboard panel.

277. In Installing Voltage Regulators they may be arranged at the end of a switchboard attached to one of the panels as shown in Fig. 195 or they can, if mounted on a standard-panel section (Fig. 189), be incorporated directly in a switchboard. It is also feasible to mount a unit like that of Fig. 190 on the front of a switchboard.

SECTION 13

SWITCHBOARDS AND SWITCHGEAR

278. The Distinction Between "Switchboard" and "Switchgear" should be understood. By definition "switchgear constitutes the parts or appliances, collectively, which make up a complete equipment for controlling and metering the elec-

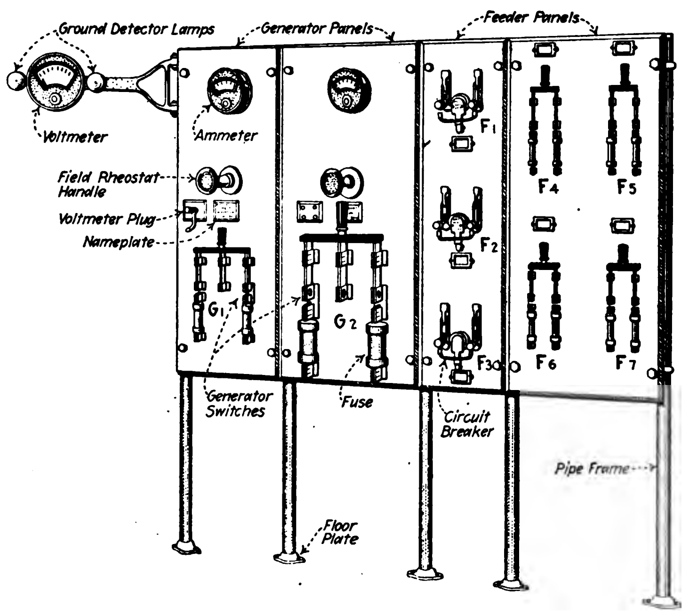


FIG. 196.—Small "standard-unit" switchboard for two compound-wound direct-current generators and seven feeders. (General Electric Company.)

trical energy output or input of an electrical station or some electrical device."

279. The Function of a Switchboard may be explained thus: A switchboard is that component of a switchgear equipment on which are mounted the meters, switch-control handles,

rheostat handles and similar contrivances. For the control of small amounts of power at low voltages it is, as will be shown, most convenient and economical to mount all of the switchgear on the switchboard, in which case the board is then said to be *self-contained*. Where the power output is large or at

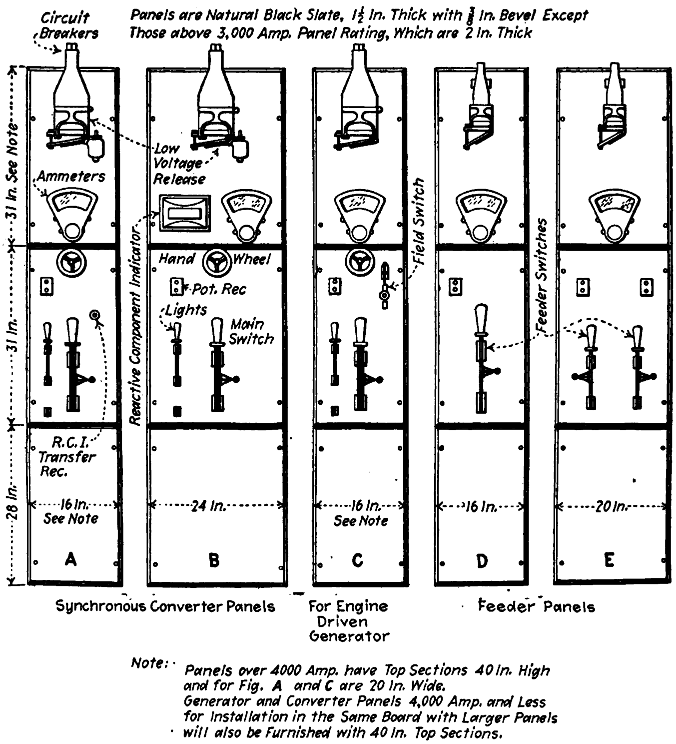


FIG. 197.—Unit switchboard panels for 600-volt, direct-current, railway service.*

high voltage, it is necessary to install certain components of the switchgear at locations distant from the switchboard proper. That is, under those conditions "remote control" is utilized. A switchboard which involves remote control is called a *remote-control switchboard*. However, in general, the control is always effected from and by means of switches, meters and appliances on the switchboard.

* General Electric Company.

280. Switchboards May Be Divided Into Four Classes: Panel switchboards (Figs. 196 and 197); control-desk switchboards (Fig. 198); pedestal switchboards (Figs. 199 and 200); and post switchboards (Fig. 201).

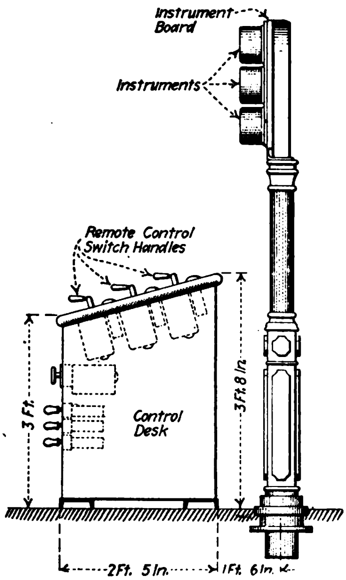


FIG. 198.—End elevation of the control desk and instrument board.

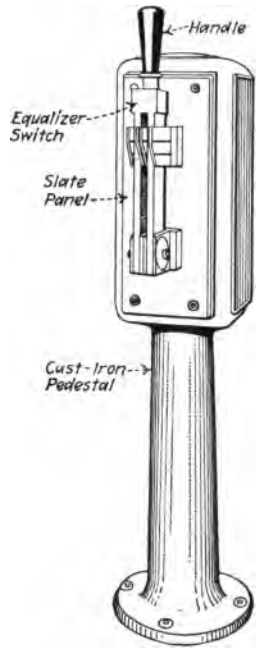


FIG. 199.—Westinghouse equalizer pedestal with switch for compound-wound direct-current generator.

281. A Panel Switchboard (Figs. 196 and 197) is one composed of panels of insulating material supported on a suitable iron framework. The various switches, instruments, rheostat handles and other control appliances are mounted on these vertical panels. Each panel is, for the larger switchboards, composed of *sections*. The panels are mounted side by side to constitute a complete switchboard.

282. The Procedure in Laying Out a Switchboard is indicated in an elementary way in Figs. 202, 203, 204 and 205.

ing panels or tie-bus panels may be inserted between the generator and feeder panels as shown at *T*, Fig. 206.

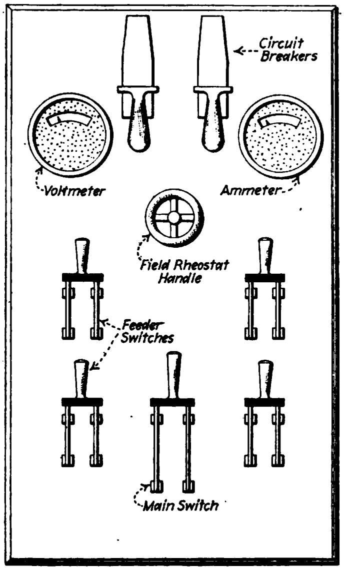


FIG. 204.—Front view of switchboard panel for a single compound-wound direct-current generator.

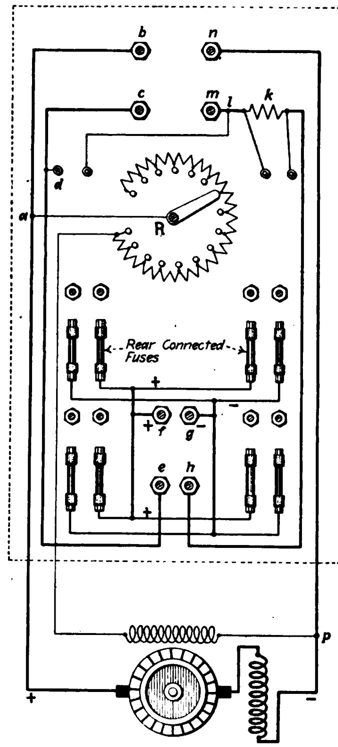


FIG. 205.—Phantom view of the switchboard panel for the compound-wound generator as it would appear if the panel were removed exposing the connections behind.

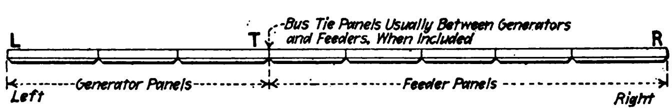


FIG. 206.—Showing usual arrangement of switchboard panels.*

284. The Proportions of Switchboard Panels and Sections have, in the United States, been fairly well standardized for

* General Electric Company.

self-contained switchboards. Panels for switchboards of medium or large capacity are almost universally made 90 in. high (Fig. 197). The "unit" sections of a 90-in.-high switchboard are, in accordance with the practice of one manufacturer, of the heights indicated in Fig. 197. Where only two sections constitute a panel, the lower slab may be 25 in. high and the upper slab 65 in. A different manufacturer uses a 62-in.-high upper slab and a 28-in.-high lower slab. The general practice is now, however, to always use three sections for 90-in.-high panels, in which case the section heights may be as shown in Fig. 197, or instead, the upper section may be 20 in. high, the middle section 45 in. and the lower 25 in. high.

NOTE.—It has been explained that the reason why these particular dimensions were adopted is that a 20-in.-high section at the top is of ample proportions to support the standard brush-type carbon circuit-breaker, which is often located at the top on the switchboard so that the arc which rises from it, when it operates under load, cannot do damage. The heights of small single-section panel switchboards like that of Fig. 196 have not been thoroughly standardized. One company uses a height overall of 5 ft. 4 in., where feasible, for boards of this general design.

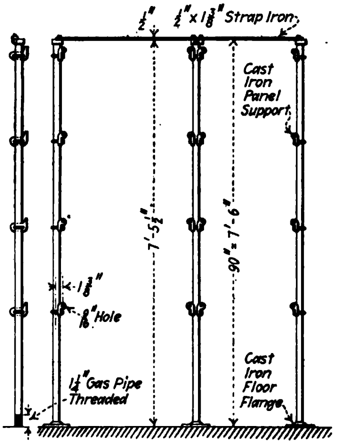


FIG. 207.—Wrought-iron pipe frame for switchboard.*

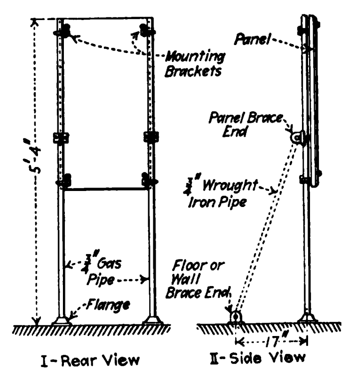


FIG. 208.—Wrought-iron pipe support for small panel.

285. The Frames for Panel Switchboards are made either of wrought-iron pipe or structural-steel sections. The com-

* Westinghouse Elec. & Mfg. Co.

ponents of the pipe frames are shown in Figs. 207 and 208 for 90-in. and 64-in.-high boards respectively. The pipe frames appear to be becoming more popular. The general construction is apparent from the illustration. Standard angle-iron frames are constructed as illustrated in Fig. 209. The angle-

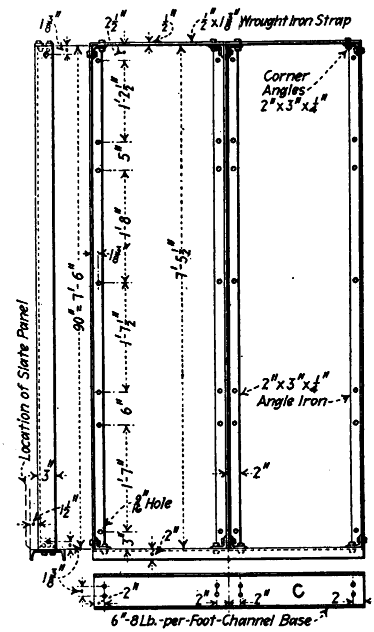


FIG. 209.—Angle-iron frame for switchboard.*

iron frame provides a very rigid support for the switchboard panel. In every installation a substantial channel base, *C* (Fig. 209), should be provided to form a level and substantial footing on which the upright pipe or single members which support the panel can rest.

286. Fittings for Supporting Switchgear, sometimes called "switchgear details," can now be obtained in many different designs, some one of which will satisfy almost any condition. Figs. 210 and 211 show typical forms. The drawing of Fig. 211 details the fittings for an iron pipe brace which may be

* Westinghouse Electric & Mfg. Co.

used for bracing a panel to the floor, as shown in Fig. 208, or for attaching it to a wall.

287. The Material for Switchboard Panel Sections must be

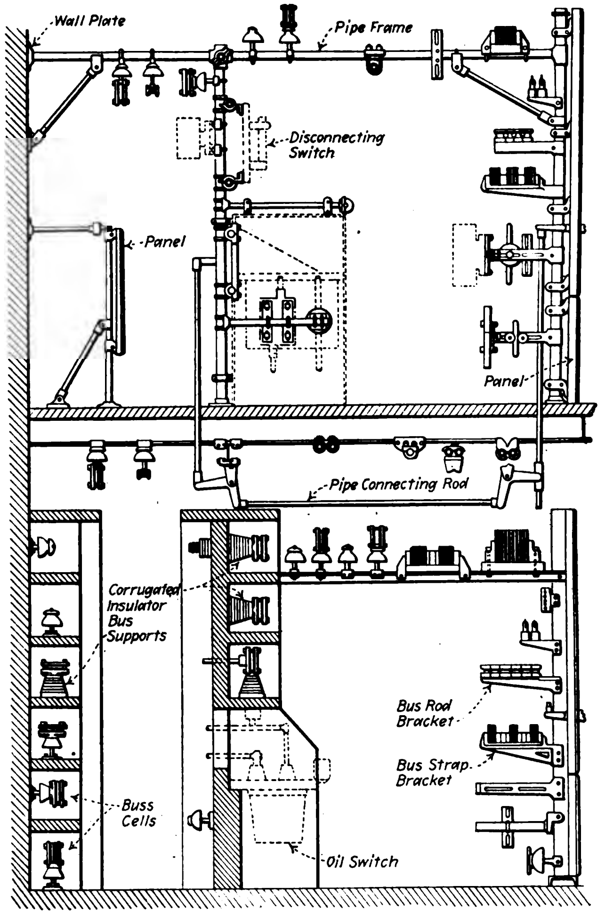


FIG. 210.—Fittings and appliances which are regularly manufactured for switching installations.*

an insulator. Either slate or marble is now ordinarily used for this service. Slate costs less than marble and is stronger but is not as good an insulator; therefore, where the pressure

* Electric Journal, May, 1913, p. 82.

for which insulation must be provided is more than 750 volts or less than 1,100 volts the use of marble is imperative. However, modern switchboards (even those for the control of apparatus operating at the highest commercial voltages) do not have extending through them, conducting members the difference of potential between which exceeds 110 volts. Even for 2,400 and 6,600-volt switchboards the oil switches, the instrument transformers and the other members upon which line voltage is impressed are thoroughly insulated from the switchboard sections.

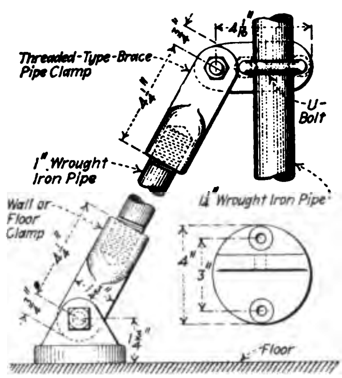


FIG. 211.—Wall or floor brace.

NOTE.—Therefore, slate sections can, from an electrical standpoint, be used for practically any switchboard. The marble sections soil easily and are, under certain conditions, almost impossible to clean. The black-finished slate panels will always look well if reasonable attention is given to them. There does not appear to be any justification for the use of marble as a switchboard section material except in display installations.

288. Panel Switchboards Are Used more frequently than those of any of the other types because of their adaptability to the many different conditions. They may be utilized for the control of practically any direct or alternating-current installation. However, as will be explained, switchboards of the pedestal, post and control-desk types may be desirable or necessary for large or complicated installations. Self-contained panel switchboards may be used where the voltage does

not exceed 6,600. Remote-control panel switchboards can be used for equipment operating at higher voltages.

289. Post Switchboards (Fig. 201) are practically always of the remote-control type. They may be used in large installations wherein they may be so located that they can be readily observed by the operator without obstructing his general view of the station interior.

290. Pedestal Switchboards (Figs. 199 and 200) are sometimes called control pedestals. These of the type suggested in Fig. 200 are used in conjunction with instrument posts for controlling generator or feeder circuits. One pedestal may be provided for each generating unit, which minimizes the possibility of the switchboard operator effecting misconnections. The pedestals are sufficiently low that they do not interfere with the operator observing the interior of the entire station. Equalizer pedestals (Fig. 199) are used for supporting the equalizer switches for compound-wound direct-current generators. Such a pedestal may be located near each large direct-current generator so that the cost of the relatively large cables to the switchboard proper, which would otherwise be necessary, is eliminated. The application of an equalizer pedestal is shown in a following illustration under the heading "600-volt Railway Switchboards."

291. Control-desk Switchboards (Fig. 198) are always of the remote-control type and are ordinarily desirable only for large installations. The instruments are usually arranged on vertical panels. In the face of the control desk are arranged the remote-control switches and indicating lamps and on its face is frequently mounted a miniature bus structure whereby the operator can observe at any time the conbination of interconnections then existing between the generating and converting equipment in the station and the lines or feeders radiating from it.

292. Direct-current Switchboards are practically always of the panel self-contained type, with the exception that equalizer pedestals (Fig. 199) may be, in large installations, used in combination with them. (The statements just preceding apply to direct-current switchboards for pressures not exceed-

ing 600 volts. Recently direct pressures of 1,200, 1,500, 2,400 and 3,000 volts have been proposed for long-distance electric railways. With these relatively high voltages remote-control switchboards of either the mechanical or electrical types may, under certain conditions, be desirable.

293. Direct-current Switchboards for Small-capacity Installations may be of the general single-section panel design suggested in Fig. 196, which shows a switchboard for the control of two compound-wound generators and seven feeders.

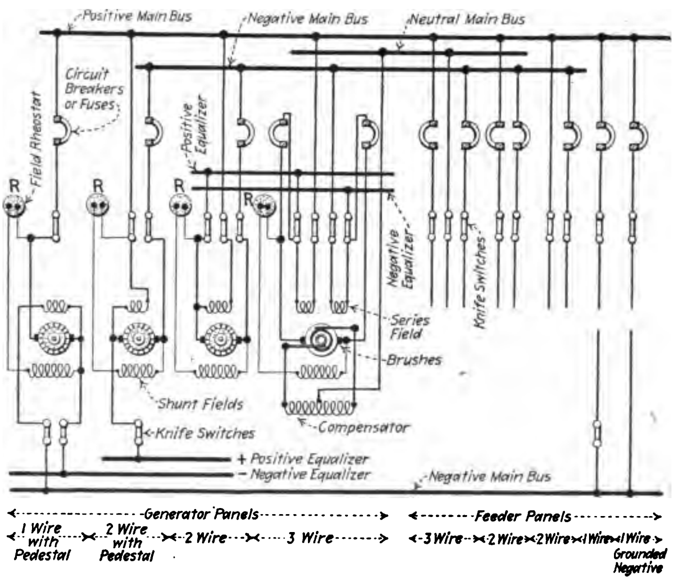


FIG. 212.—Typical low-voltage, direct-current, switch-board connections.

G_1 and G_2 are the generator switches. The middle blade of each of these switches is in the equalizer lead and is unfused. The feeders F_1, F_2 and F_3, for the motors, are protected by circuit-breakers. The lighting feeders, F_4, F_5, F_6 and F_7 are protected by enclosed fuses.

294. Direct-current Switchboards for Installations of Medium and Large Capacity, are practically always of the three-section panel type (Fig. 197) and are 90 in. high.

295. The Essential Circuit Diagrams for Direct-current

Switchboards are shown in Fig. 212. This indicates how two-wire and three-wire generators are connected and how one-wire, two-wire and three-wire feeders may be arranged.

296. A Moderate-capacity, Two-wire, Direct-current Switchboard is shown in Figs. 213, 214 and 215. These illustrations* show the general construction of a unit section,

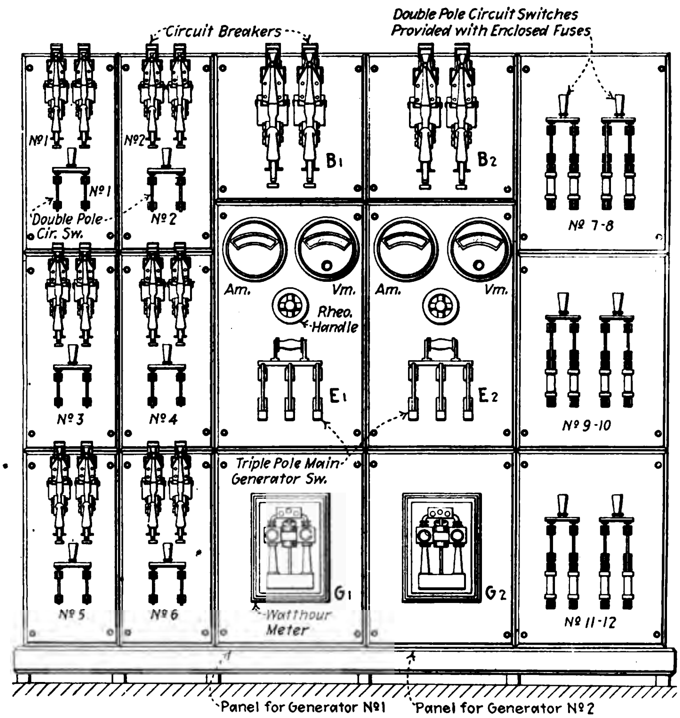


FIG. 213.—Front view of the five-panel direct-current switchboard.

direct-current switchboard for a medium-capacity, isolated-plant installation operating at a pressure of 110 volts. Fig. 216 shows the connection diagram. Each lighting feeder is controlled by a double-pole knife switch protected with enclosed fuses. Each motor feeder is controlled and protected by a double-pole automatic circuit-breaker. Each of the two

* Roland, APPLIED ELECTRICITY FOR PRACTICAL MEN, p. 100.

generators has its own panel and is protected by a double-pole circuit-breaker, B_1 and B_2. In a moderate capacity installation such as this the equalizer lead from each generator is carried to the switchboard and connected to the center blade, E_1 and E_2 (Fig. 213) of the main switch.

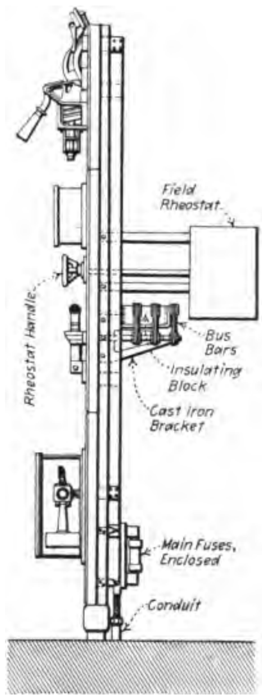


FIG. 214.—Vertical section taken just to the right of one of the generator panels.

297. Large-capacity Two-wire Direct-current Switchboards are usually arranged so that an isolated equalizer pedestal (Fig. 199) may be used for economic reasons above outlined. Fig. 217 diagrams typical connections for a generator panel of this type. The generator panel itself is illustrated in Fig. 218. The feeder panels are usually constructed about as shown in Fig. 219.

298. Three-wire Direct-current Switchboards resemble, in general external appearance, those for two-wire circuits. The connections, however, are materially different in certain details, as disclosed by Fig. 220. This delineates the circuit arrangement for a switchboard seıving two three-wire 110–

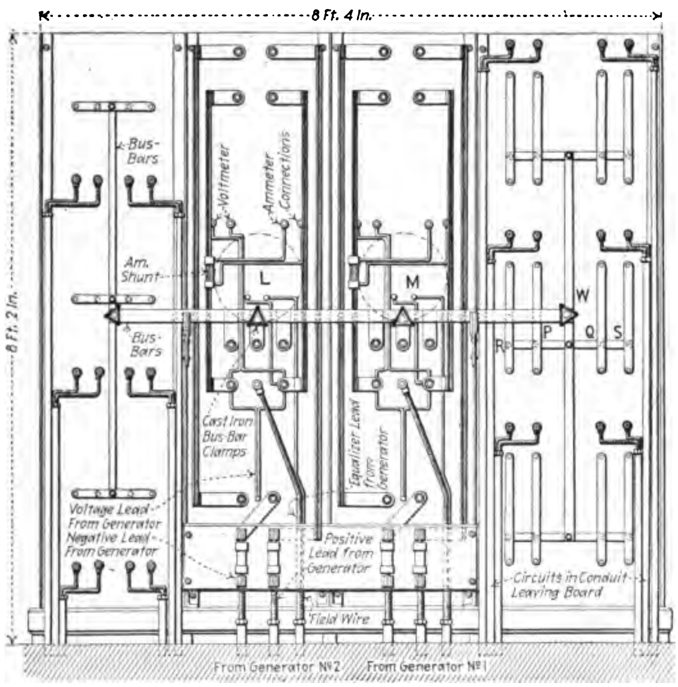


FIG. 215.—Rear elevation of the five-panel direct-current switchboard.

220-volt direct-current generators and three feeders, one of the feeders being 220-volt two-wire.

299. Switchboards for 600-volt Direct-current Railway Service are really two-wire switchboards but due to the fact that a ground return is almost always used for railway circuits, certain variations from the standard two-wire construction is necessary. Only one side of the circuit, usually the positive, is carried to the switchboard as illustrated in

Fig. 221. Both the equalizer switch and the negative switch, if such is used, may be mounted on a pedestal, P_1 and P_2 (see Fig. 199 for detail) located near the machine. The negative side of the line is carried to a ground connection near the pedestal. Hence, in effect, the earth itself constitutes the negative bus. By utilizing this *"single-bus" design* material

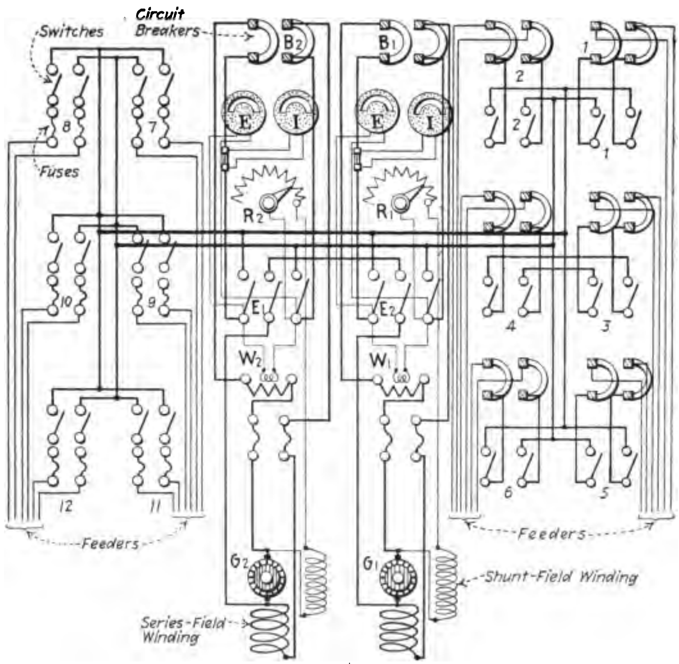


Fig. 216.—Wiring diagram for the five-panel direct-current switchboard.

economies in first cost are realized. Both the generator and feeder panels (Fig. 197) can then be made narrower because only a single-pole switch is necessary on the panels. This tends to reduce the cost of the switchboard. A further economy results from the fact that with the single-bus arrangement it is not necessary to route the heavy negative and equalizer conductors to the switchboard.

300. Alternating-current Switchboards may be divided into two general classes: (1) self-contained, and (2) remote-control.

The remote-control boards can be further subdivided into: (*a*) *mechanical remote-control,* and (*b*) *electrical remote-control.* It is usually good practice for all except extraordinary conditions, to use self-contained switchboards for alternating-current service at pressures not exceeding 6,600 volts where the capacity of the station does not* exceed about 3,000 kva. Where the capacity or the voltage exceeds the value just noted,

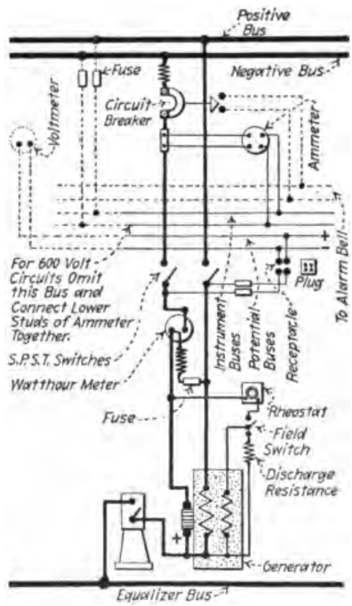


FIG. 217.—Low-voltage direct-current generator panel wiring where equalizer pedestal is used. (Back view.)

remote-control equipments should be used. A feature which distinguishes alternating from direct-current switchboards is that it is standard practice to use oil switches instead of air-break switches for rupturing the alternating-current circuits on voltages as low as even 240. Inasmuch as the three-phase system is now adopted for almost every energy-generating and transmitting installation, a majority of the alternating-

*C. H. Sanderson, "SWITCHBOARDS FOR ALTERNATING-CURRENT POWER STATIONS."

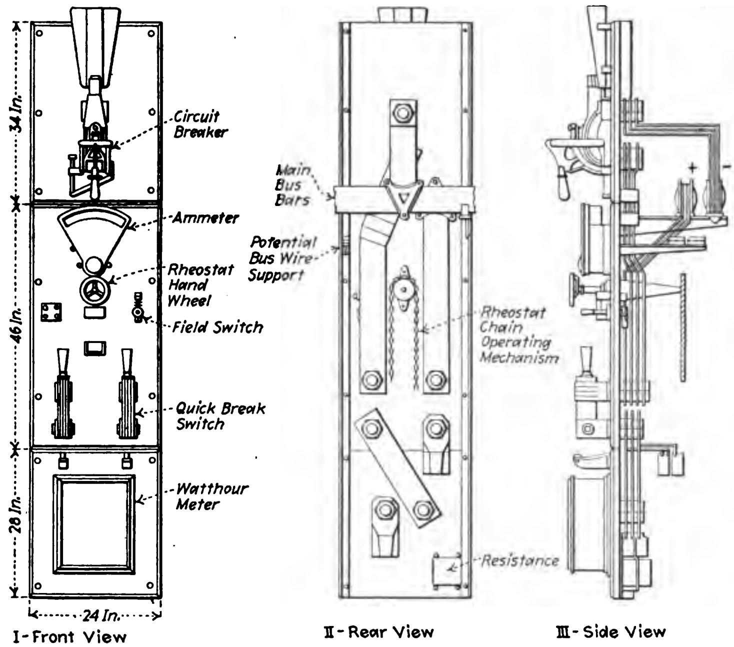


FIG. 218.—Low-voltage, direct-current, two-wire generator panel of large capacity.

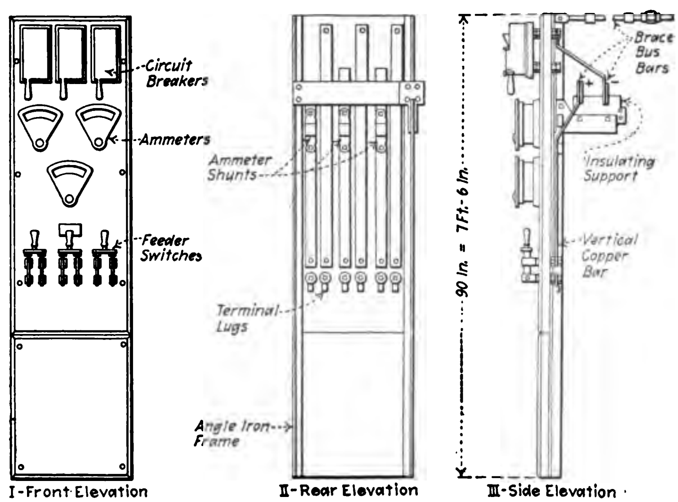


FIG. 219.—Typical direct-current feeder panel in an installation of considerable capacity.

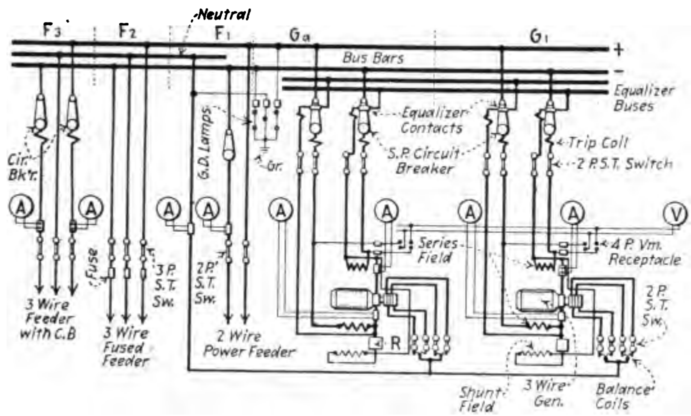


FIG. 220.—Wiring diagram for a three-wire, direct-current switchboard serving two generators and three feeders.

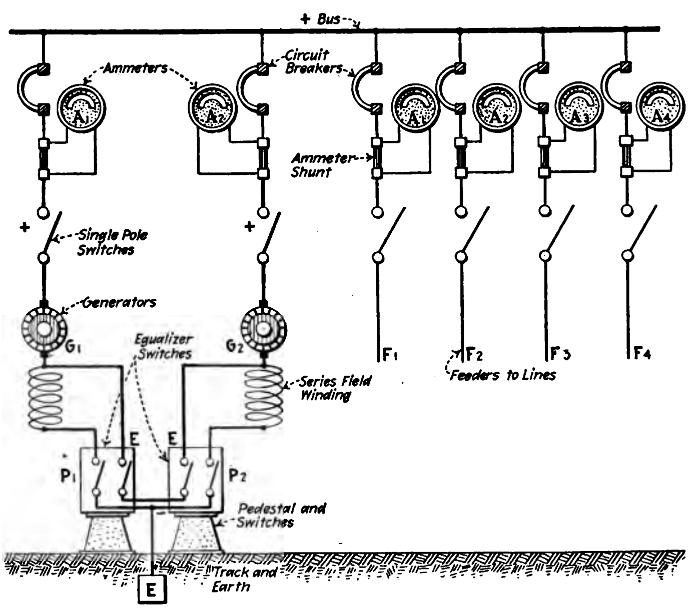


FIG. 221.—Typical connection diagram for a 600-volt, direct-current railway switchboard.

current switchboards which are now installed are for three-phase service.

301. Alternating-current Switchboards for Three-phase 240- and 480-volt Service are (except those of great capacity) nearly always self-contained. The wiring diagram for a typical outfit of this character is shown in Fig. 222. The general appearance of such a board would be the same as that for a 2,400-volt board shown in Fig. 223. It should be noted

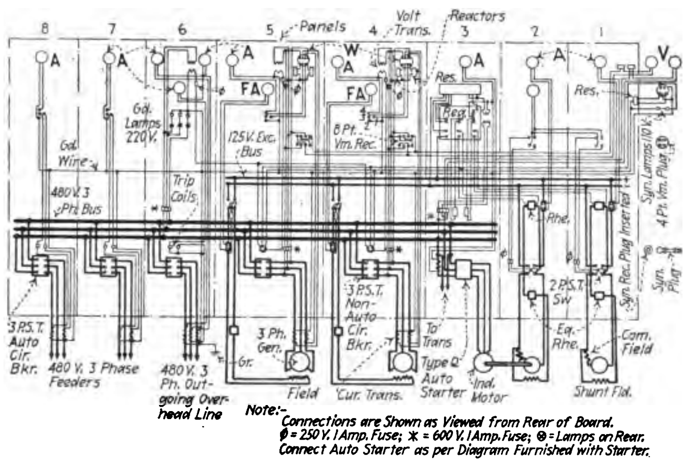


FIG. 222.—Typical wiring diagram for a 240- or a 480-volt switchboard.*

that oil switches are used for the three-phase switches in this installation.

301A. Switchboards for 2,200 to 2,400-volt Three-phase Alternating-current Service† are also nearly always self-contained. Figs. 223, 224 and 225 show the external appearance of a typical switchboard of this character while Fig. 226 delineates the detailed wiring diagram. Fig. 227 shows a single-line diagram of the board. This equipment is typical of that which would be used in a central station which supplies light and power to a small city. Two generators, G_1 and G_2 (Fig. 227), and two exciters, E_1 and E_2, serve, together,

* Westinghouse Electric & Manufacturing Co.

† C. H. Sanderson, "SWITCHBOARDS FOR ALTERNATING-CURRENT POWER STATIONS."

four feeders, F_1 to F_4. Panels 1 and 2 are the combination generator-and-exciter panels. An automatic voltage regulator is mounted at the end of the board on panel No. 1. Panel 3 serves two three-phase power feeders. Panel 4 con-

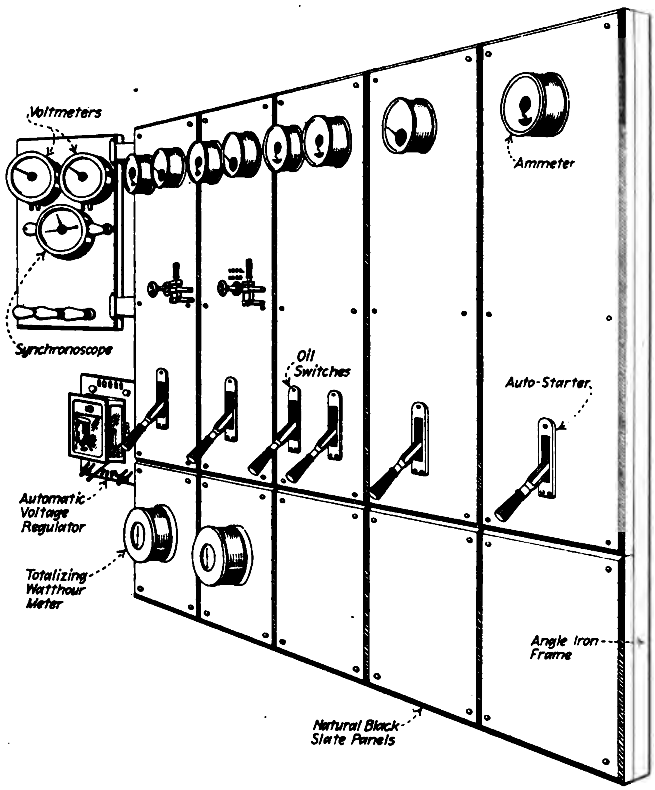


FIG. 223.—Perspective view of the typical 2400-volt, three-phase switchboard for power and lighting service in a small town.

trols the rectifier circuits for the series direct-current arc lighting. Panel 5 carries the auto-starter and ammeter for the alternating-current motor end of a synchronous motor-generator set which supplies the town with direct current. Less expensive switchboards of the general construction indi-

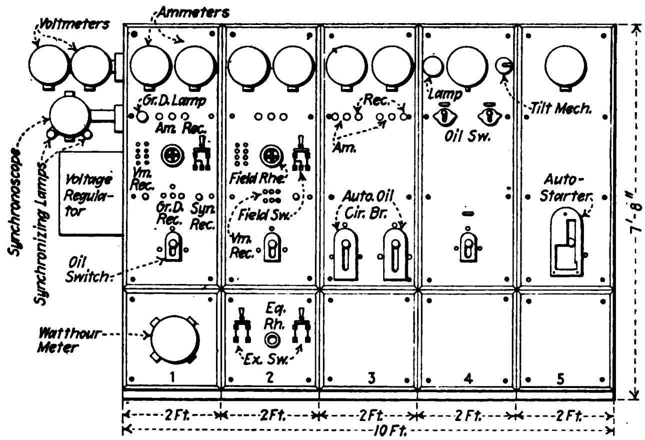


FIG. 224.—Front view of the 2400-volt, three-phase lighting and power switchboard.

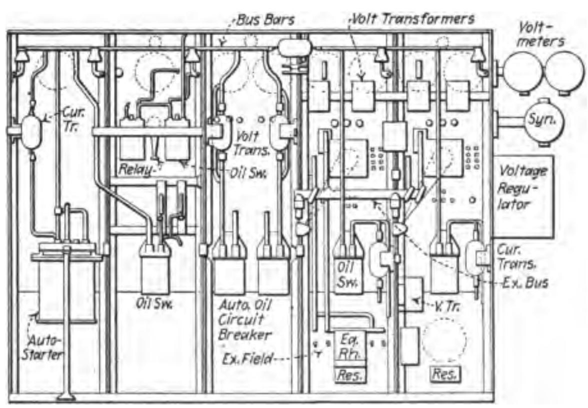


FIG. 225.—Rear elevation of the switchboard the perspective and front views of which are shown in other illustrations.

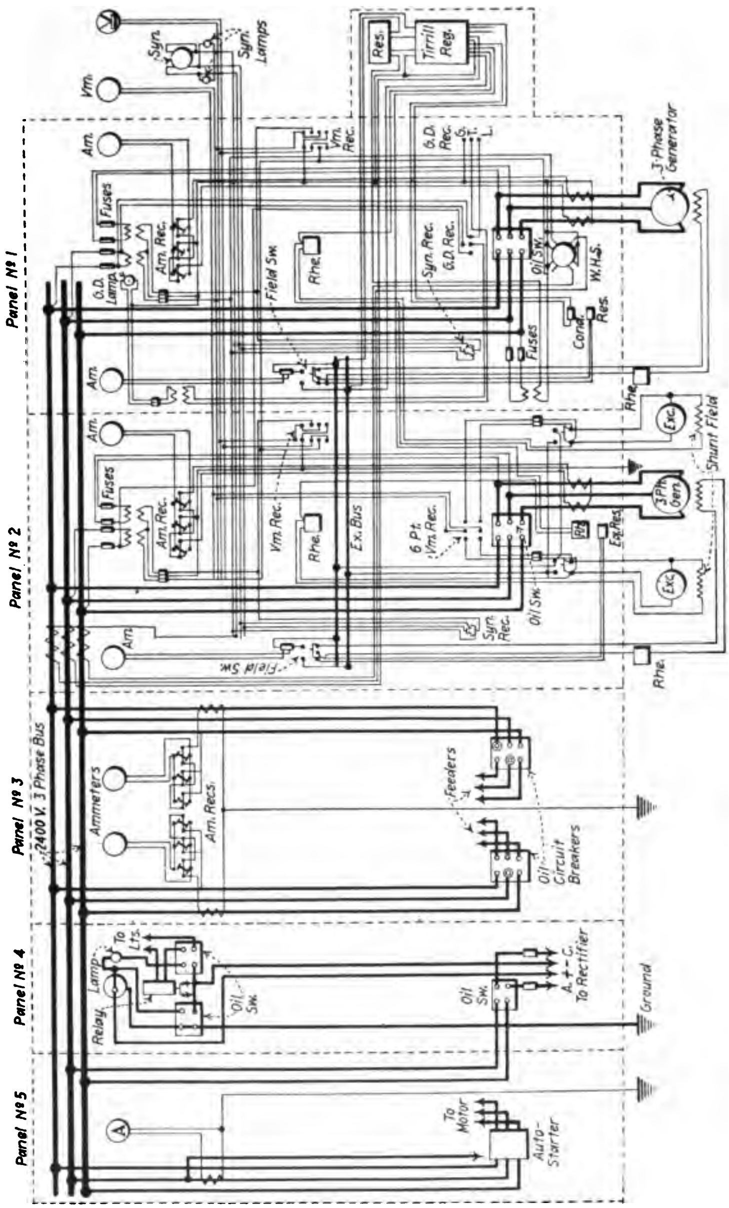


FIG. 226.—Connection diagram of the switchboard of Figs. 223, 224 and 225.

cated in Fig. 196 may be purchased for simple alternating-current installations but inasmuch as plenty of room is desirable on an alternating-current switchboard the 90-in.-high type (Fig. 223) is usually preferable.

NOTE.—The advantages accruing through the use of remote-mechanical-control switchboards as compared with self-contained switchboards have been thus summarized by C. H. Sanderson in his SWITCHBOARDS FOR ALTERNATING-CURRENT POWER STATIONS: (1) All high voltages are removed from the panels, thus permitting ready inspection of the instrument and control wiring, eliminating danger of injury to attendants from contact with live parts, permitting the location of the board to much better advantage as regards the remainder of the installation because less space and less protection are required. (2) Panels are not subject to the mechanical strains due to automatic operation or to the dead weight of the apparatus. (3) In case of marble panels their appearance is not marred by stains from creeping oil. (4) Violent explosions which sometimes occur upon the opening of heavy currents or the possible failure of a circuit-breaker will not injure the panels and, if the circuit-breakers are sufficiently spaced or are enclosed in fireproof cells, adjacent circuit-breakers will not be affected. (5) The panels may be much narrower, the reduced cost thereof off-setting, to a considerable extent, the additional cost of the remote-control feature. Moreover, the decrease in total length of the board may result in a very material saving in cost. (6) A more compact arrangement of the apparatus is of great assistance to the operator, approaching as it does more nearly to the compact and efficient arrangements obtained by means of control desks. (7) Much shorter main connections are made possible, and high voltages kept away from certain floors, or certain rooms by locating the remote-control structure properly. (8) Where a wall is used for supporting the apparatus, the cost of the complete outfit may be reduced to very near that of the self-contained type of board, and, in some cases of very heavy capacities at low voltages, may be less in cost. Moreover, accessible arrangements of apparatus with ample spacings may easily be obtained. (9) Where a steel or masonry structure is used, access may be had to either side of the structure and an arrangement of this kind will satisfactorily accommodate the maximum amount of apparatus ordinarily used for either single- or double-throw arrangements.

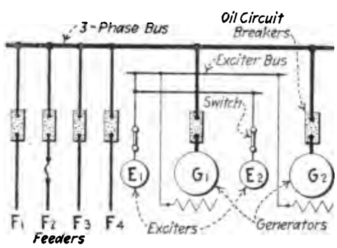


FIG. 227.—Single-line diagram of the switchboard of Fig. 226.

302. An Alternating-current Mechanical Remote-control Switchboard is shown in Figs. 228, 229, and 230. A wiring diagram is given in Fig. 231. Boards of this general design

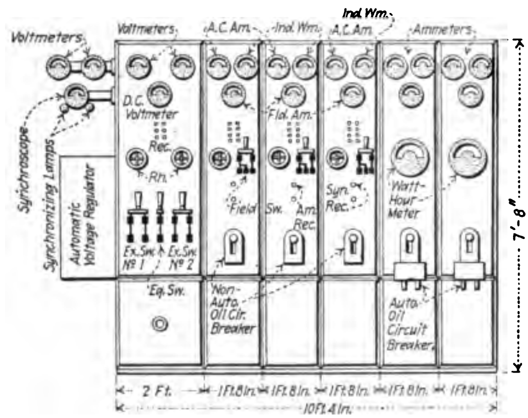


FIG. 228.—Front view of the mechanically-operated remote-control switchboard.

are suitable for applications for voltages not exceeding 35,000 and capacities not exceeding 25,000 kva. three-phase.* It should be noted that all of the alternating-current control

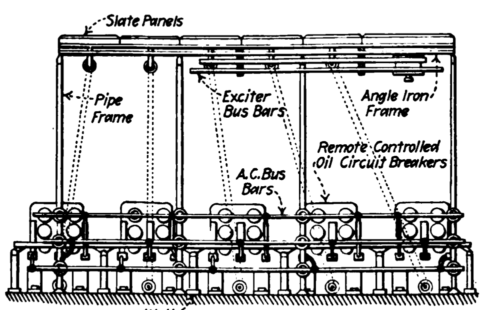


FIG. 229.—Plan view of the mechanical remote-control switchboard.

apparatus is supported on a structure independent of the switchboard panels. The control equipment can, for relatively low voltages, be supported on a wall directly back of the

* C. H. Sanderson, SWITCHBOARDS FOR ALTERNATING-CURRENT POWER STATIONS.

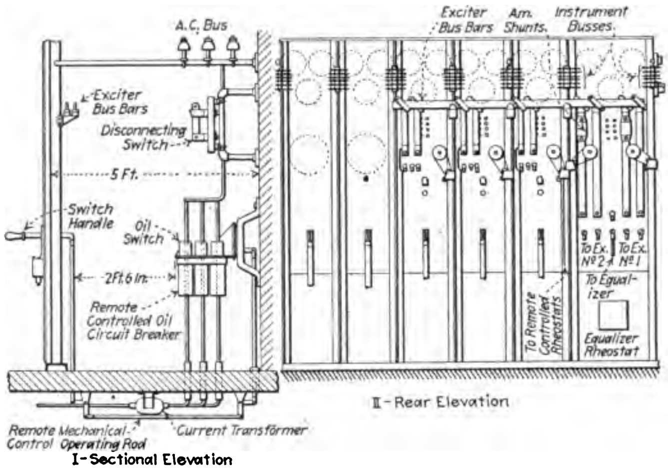
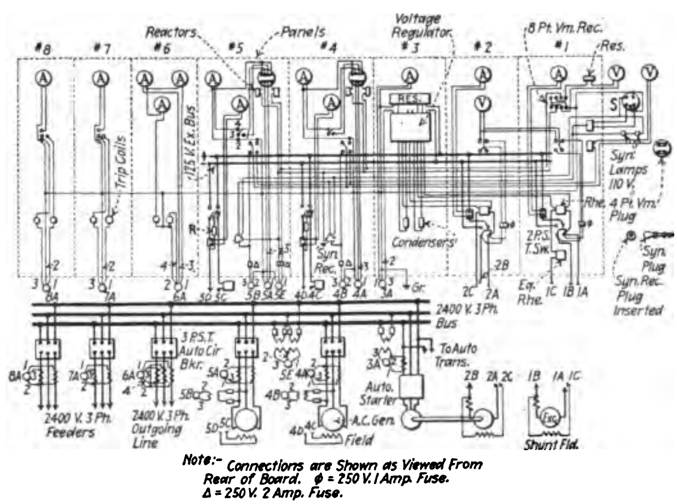


Fig. 230.—Rear view and sectional elevation of remote-control switchboard mechanically operated.



Note:- Connections are Shown as Viewed From Rear of Board. ϕ = 250 V. 1 Amp. Fuse. Δ = 250 V. 2 Amp. Fuse.

Fig. 231.—Wiring diagram for a typical mechanical remote-control switchboard.

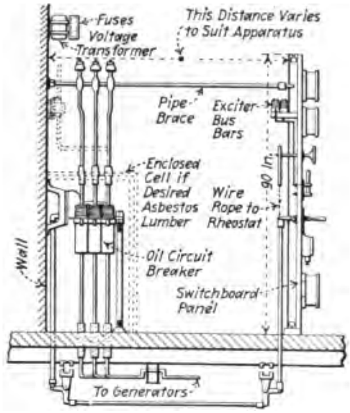


FIG. 232.—Mechanical remote-control circuit-breaker mounted on wall.

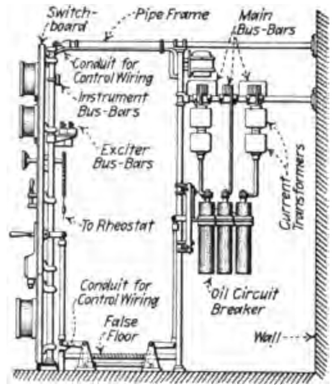


FIG. 233.—Arrangement of mechanical remote-control switchgear utilizing wall and a pipe frame for a supporting structure.*

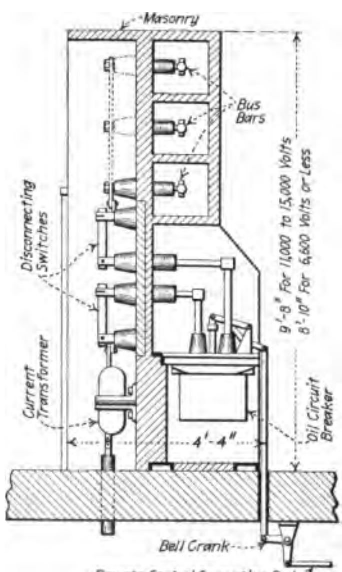


FIG. 234.—Remote mechanical oil circuit-breaker arranged in masonry structure.*

* C. H. Sanderson in "SWITCHBOARDS FOR A. C. POWER STATIONS."

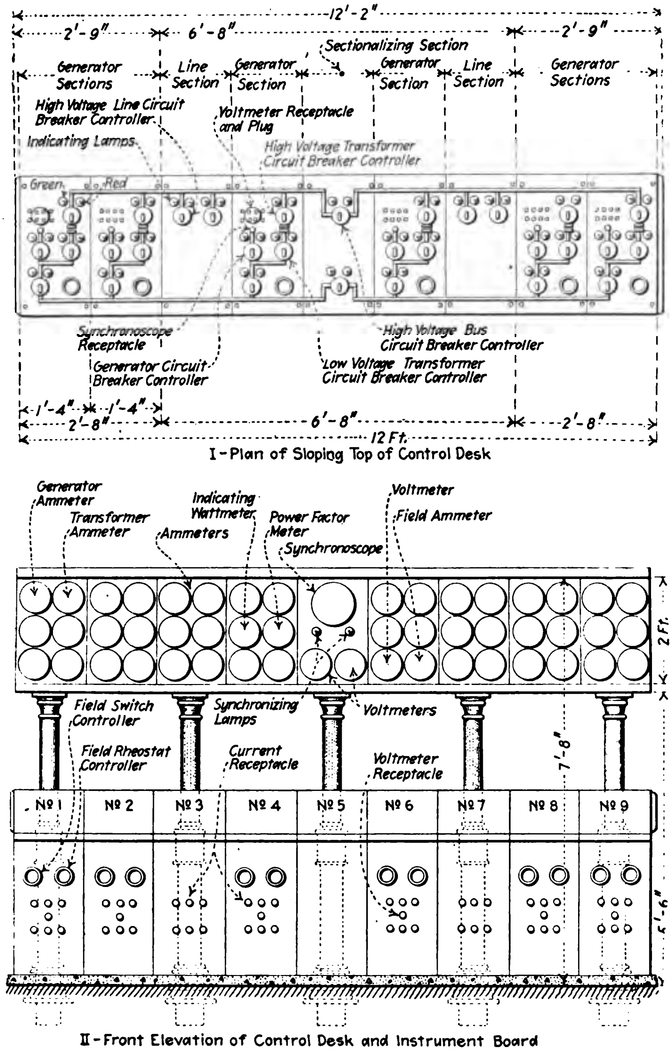


FIG. 235.—Plan of face of desk and front elevation of control desk and instrument board.

switchboard proper, as shown in Figs. 230, *I* and 232. Or it can be carried on a specially designed pipe frame (Fig. 233) back of the board. Where the voltage is relatively high and the bus structure should, therefore, be located in rooms or chambers distant from the switchboard, the circuit-breakers can be mounted in a masonry structure as suggested in Fig. 234.

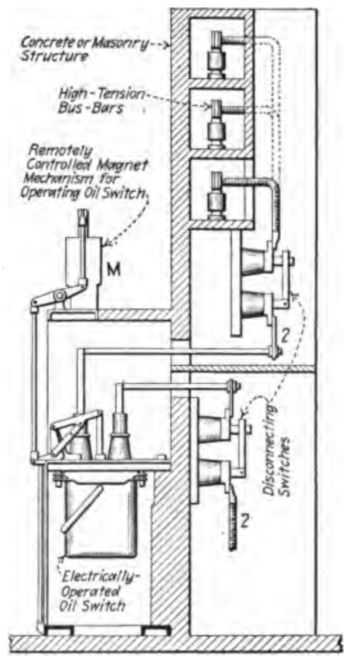


FIG. 236.—Remote-control oil switch in masonry-cell mounting.

303. Electrical Remote-control Switchboards are ordinarily used only in the largest and most important installations. The small switches which control the operation of the large oil power switches may be mounted on a panel switchboard, on a control pedestal (Fig. 200), or on a control desk (Figs. 198 and 235). The instruments are mounted on the upper part of the board where a panel switchboard is used or on an instrument pedestal (Fig. 201), where a control pedestal is

utilized. With a control desk the instruments may be mounted on posts (Figs. 198 and 235) or on a vertical upward extension of the control desk. As suggested in Art. 291, on the face of the control desk is arranged a miniature bus structure. The operation of the small switches on the switchboard permits current to flow through the magnet M, Fig. 236, of the electrically operated remote-control oil switches, whereby they may be opened or closed at the will of the operator. In general, no two electrically operated remote-control boards are alike because each is usually designed to satisfy certain specified conditions of operation. The possible variations in design are almost endless, hence cannot be considered here.

SECTION 14

CHARACTERISTICS OF ELECTRIC GENERATING STATIONS

304. The Procedure Which Will Be Followed in Describing Electrical Energy Generating Stations is this: *First,* certain general considerations relating to all generating stations, regardless of the types of their prime movers, will be treated. *Second,* the adaptability of each of the different classes of prime movers: (*a*) steam, (*b*) internal-combustion engine, and (*c*) hydraulic, will be described. *Third,* stations having steam prime movers will be studied in some detail. *Fourth,* stations having internal-combustion engine prime movers will be considered. *Fifth,* hydro-electric stations will be examined.

305. In Determining the Cost per Unit of Electrical Energy Generated by a Station a number of factors must be included. Among these may be: (1) cost of fuel, if any; (2) labor cost of attendance and operation; (3) cost of supplies, such as oil and waste; (4) interest on the investment; (5) depreciation; (6) taxes; (7) insurance; and (8) repairs. How all of these factors may be recognized in estimating the total cost is indicated in the example just following. It is obvious that each specific problem must be considered on its own merits. The reasons for this are that the efficiencies of the apparatus involved, the cost of fuel, the cost of attendance and similar elements, will vary widely under different conditions.

Example of Method of Determining Cost of Generating Energy.—The following examples are quoted to illustrate the general procedure and the principal factors involved rather than to emphasize specific values. The problem is this: *Which would be more economical under the conditions to be recited, to continue to operate a steam plant or to purchase electrical energy from a central station? The connected load is* 275 *kw. The maximum demand (maximum load) is* 230 *kw. The annual energy consumption is* 62,700 *kw.-hr. There are two generators in the plant, each driven by its own steam engine.* No. 1 *is a* 200-*kw. unit. No.* 2 *is a* 75-

kw. unit. The charge which the central station would make would be based on (1) *a "demand" or "readiness-to-serve" charge of $2 per month per kw. of connected load and* (2) *an additional "energy" charge of* 0.9 *cts.* ($0.009) *per kw.-hr. consumed. All of the connected apparatus is direct current, hence, if central-station energy is purchased, it must be direct current or be converted into direct current for utilization.*

SOLUTION.—The following comprises the solution, submitted by H. Berkeley Hackett,* to the above example. Owing to the values submitted for maximum demand and monthly energy consumption, it would be erroneous to assume the 10-hr.-day service during 26 days per month, which is the customary working period in manufacturing industries, since on this basis the average hourly load would exceed the maximum demand. In order, however, to reach any conclusion it is necessary to decide upon a daily operating period, consequently it will be assumed that the plant in question operates continuously during 365 days per year. While this assumption may not represent actual conditions, it will at least afford a basis for demonstrating the method of computing the yearly cost of generating energy and comparing same with central-station service.

The first step will be to find the boiler capacity required to meet the peak load conditions, in order that fixed charges on these units may be properly accounted for. With a maximum demand of 230 kw., the probable "water rate" of the large engine will be 40 lb. of steam per kw.-hr., consequently the hourly steam consumption under these load conditions is: $230 \times 40 = 9{,}200$ *lb.* plus 10 per cent. for auxiliaries, pipe line losses, etc., or a total of 10,120 *lb. per hr.* that the boilers must supply during maximum-demand periods.

Assuming that the steam pressure is 130 lb. gage and that the temperature of the feed water entering boilers is 200 deg., each pound of feed water must receive in the boilers 1024.8 heat units to convert into steam at the assumed pressure. Therefore, the boilers must be capable of furnishing: $10{,}120 \times 1{,}024.8 = 10{,}371{,}000$ *heat units per hr.* Since a boiler horse-power is equivalent to 33,500 heat units, the boiler capacity required will be: $10{,}371{,}000 \div 33{,}500 = 310$ *h.p.* Three 150 h.p. water-tube boilers will therefore be considered in estimating the installation costs.

The second step in the calculation will be to determine the yearly coal requirements. With a monthly consumption of 62,700 kw.-hr., the average hourly load of 24-hr. service will be: $62{,}700 \div 24 \times 30 = 86$ *kw.* approximately. To allow for load fluctuations on engines and boilers, it will be assumed that the water rate of the engines is 45 lb. of steam per kw.-hr., and that the boilers evaporate 6 lb. of steam per lb. of coal. This evaporation corresponds to 51 per cent. boiler efficiency, assuming the heat value of the fuel to be 12,000.

* "CALCULATING COST OF POWER AS GENERATED BY STEAM, *Electrical Engineering*, January, 1915, p. 41.

On a basis of 8,760 hr. per year, the total yearly steam requirements, including 10 per cent. for auxiliaries, pipe-line losses, etc., will therefore be: 86 × 45 × 8,760 × 1.1 = 37,291,000 *lb.*, and since each pound of coal evaporates 6 lb. of steam, the coal necessary to evaporate this quantity of steam is: 37,291,000 ÷ 6 = 6,215,100 *lb.*, or 3,110 *short tons.*

Having determined the boiler capacity and the yearly coal requirements it is possible to approximate the yearly operating costs, as given in the following tabulation:

INSTALLATION COST

Apparatus	Cost	Sub-totals
One 120-h.p., 4-valve engine (erected)	$2,600	
One 320-h.p., 4-valve engine (erected)	5,800	
Foundations	750	
Three 150-h.p. water-tube boilers (erected)	7,500	
Steel stack foundation—breeching erected	2,000	
Feed-water heater—boiler feed and house pumps.	1,000	
Piping—covering separators, tanks, etc	4,000	$23,650
One 75-kw. direct-current generator erected	1,100	
One 200-kw. direct-current generator erected	3,000	
Switchboard and wiring	1,700	5,800
Total cost of plant	....	$29,450

GENERATING COST

Interest on $29,450 @ 5 per cent	$1,470	
Depreciation on 29,450 @ 6 per cent	1,770	
Taxes, insurance, etc., on $29,450 @ 1 per cent.	295	$3,535
Fuel, 3,110 tons @ $3	9,330	
Labor (5 operators)	4,600	
Ash hauling	100	
Oil waste, etc	300	
Maintenance and repairs	600	$14,930
Total annual cost of generating 67,200 × 12 = 752,400 kw.-hr.	....	$18,465
Cost per kilowatt-hour, in cents = 18,465 ÷ 752, 752,400 =	....	2.46

Cost of Central-station Service

The connected load is 275 kw. The primary charge will be \$2 per month. The average monthly energy consumption of 62,700 kw.-hr. will be at the rate of 0.9 cts. per kw.-hr. If a rotary (synchronous) converter is installed, the customer will probably, be required to pay the conversion losses. With a converter efficiency of 90 per cent., the monthly bill charged against the consumer will therefore be: $62,700 \div 0.9 = 69,500$ kw.-hr. The annual cost of purchased power will therefore be about as follows:

Installation Costs

One 250-kw. rotary converter..................	\$3,000	
Switchboard................................	1,700	
Total installation cost.........................	....	\$4,700

Operating Costs

Interest, depreciation, etc., @ 12 per cent. on \$4,700..................................	\$560	
Primary charge—275 × 12 months × \$2........	6,600	
Current charge—69,500 × 12 × \$0.009.........	7,500	
Night and day attendant......................	1,700	
Oil, waste, repairs, etc........................	70	
Total yearly cost of 69,500 × 12 or 834,000 kw.-hr....................................	....	\$16,430
Cost per kilowatt-hour in cents................	....	1.97

In the above estimates no consideration has been given the question of heating. Should the conditions demand this requirement, it will be necessary to make certain additional charges against the central-station estimate in order to obtain a true comparison of power costs. These charges would consist of interest and depreciation on boiler capacity for heating, corresponding to the boiler capacity, available in the private plant for this purpose. Also, a charge for fuel for generating steam, equivalent in amount to the exhaust steam from the engines of the private plant that could be utilized in the heating system. There would be a further charge for labor, maintenance, supplies, etc., in connection with the operation of boilers for heating.

The following table illustrates a logical and systematic method of tabulating the fixed-charge data when an energy-cost determination is being made. This table shows the values assumed by T. B. Hyde in his solution of the example above proposed. For this complete solution refer to the number of the magazine cited in the footnote.

STEAM PLANT (*Energy Generated*)

A	*B*	*C*	*D*	*E*	*F*	*G*	Fixed charges (per cent.)					*N*
							I	*J*	*K*	*L*	*M*	
Item	Equipment	Number	Size	Unit	Unit cost	Total cost	Interest	Depreciation	Insurance taxes	Maintenance (repairs)	Total	Fixed charges per year
1	Boilers....	3	150	B.H.P.	$14.00	$6,300	5	5	1½	6½	18	$1,134
2	Engine....	1	320	I.H.P.	11.00	3,520	5	5	1	3	14	493
3	Engine....	1	120	I.H.P.	10.00	1,200	5	5	1	3	14	168
4	Generator	1	200	K.W.	12.50	2,500	5	5	1	1	12	300
5	Generator	1	75	K.W.	13.35	1,000	5	5	1	1	12	120
6	Building...	..	...	....	......	9,000	5	3	1	1	10	900
7	Feedpump	..	...	....	......	200	5	7	1	3	16	32
8	Feed-water Heater	..	400	H.P.	1.50	600	5	5	1	3	14	84
9	Piping.....	..	...	....	......	2,000	5	7	1	3	16	320
10	Total											3,551

ELECTRIC PLANT (*Energy Purchased*)

11	Building...	..	...	....	......	$3,000	5	3	1	1	10	$300
12	Synchronous converter.	..	...	....	......	2,000	5	5	1	1	12	240
13	Total....											$540

NOTE.—DEPRECIATION OF THE EQUIPMENT OF AN ELECTRIC PLANT.*— In general, plant and sub-station buildings may be assumed to have a useful life of about 50 years, making the average depreciation about 2 per cent. To boilers, piping, generators, electrical equipment, etc., lives of 20 years are assigned. Of these, boilers, piping and generators have net salvage values of 4 to 6 per cent. at the end of that time, thus making their rate of depreciation from 4.7 to 4.8 per cent. per annum. Allowing 10 per cent. salvage value for electrical equipment, the rate of depreciation becomes 4.5 per cent. Storage batteries, with a useful life of 20 years, go out of service with a salvage value of 17 per cent. mak-

* *Electrical World.*

ing the net depreciation 4.15 per cent. per year. Poles and pole-line equipment are assigned values of 12 per cent. at the end of 20 years' service, resulting in a depreciation rate of 4.4 per cent. Wire, after 16 years' estimated usefulness, has the high scrap value of 40 per cent., making the depreciation rate 3.75 per cent. Line transformers and customers' meters may be assumed to have the same life as the other electrical equipment named, 20 years, but at the end of that time they have a salvage value of 10 per cent., making the net depreciation rate in the case of these instruments 4.5 per cent.

306. The Location of a Generating Station is a thing which should be considered most carefully, because if the station is not located intelligently the cost of the energy generated and delivered by it may be excessively high. In this connection the following items* are of importance: (1) accessibility. (2) coal and water supply, (3) stability of foundation, (4) facilities for extension, (5) cost of real estate and taxes, and (6) situation should be such that the output of the plant may be effectively utilized.

NOTE.—The station should, all things being equal, be easily accessible so as to facilitate the delivery of fuel, stores and machinery, while it should be so located that the ashes may be easily removed. If possible, the station should be so located that it may be reached by both rail and water.

307. The Advantages of Centralization, that is, the advantages which accrue through the concentration of generating equipment into one large plant rather than having it scattered among a number of small plants may be recited thus:* (1) It is possible to distribute the power economically, (2) because of the diversified nature of the load it is possible to operate the system with a better load factor, (3) purchasing supplies and spare parts at a central point is a decided economic advantage, (4) the centralization of management and operating force reduces the overhead expenses, (5) it is possible to serve certain classes of customers whom the small individual plant could not afford to serve, (6) the lower cost of production, due to centralized service, makes it possible to offer lower rates, (7) consolidation of interests makes possible the financing of im-

* THE LOCATION OF POWER PLANTS, by J. M. Kearns of the Boston Edison Company.

provements, of substitution of new for obsolete apparatus and the extension of service into new territory and (8) better regulation and better protection can be provided.

308. Direct-current Voltages and Systems may be divided into two-wire and three-wire systems. Two-wire systems (which are, ordinarily, desirable only for electric-lighting service where the power is transmitted over very short distances) usually operate at 110 volts because 110 volts is, due to economic reasons, the most desirable pressure for operating incandescent lamps in multiple. Occasionally, in a direct-current installation, where the power must be transmitted for a distance of possibly something under a mile for direct-current motors, a 220-volt direct-current system may be installed. If this is done, 220-volt incandescent lamps are used. It is seldom that a two-wire direct-current system is now installed for general electric lighting and power service. Usually, because of the economics which result therefrom, a three-wire system is used. The pressure between the outer wires is 220 volts and between the neutral and each of the outers, 110 volts. With this system, the incandescent lamps can operate on 110 volts and the motors on 220. The stations in many office buildings, industrial plants and small towns generate on 110–220-volt three-wire system. For urban railway service, the standard direct-current pressure is 600 volts. Pressures as high as 1,200, 2,400, 1,500 and 3,000 volts have been applied recently for interurban and trunk line railway service.

308A. The Generation of Alternating Voltages is now, in stations serving large cities or considerable loads of any character, the usual practice—because of the economies which result therefrom. Then, if at any location on the distribution system, direct current is required, the alternating can be converted into direct voltages by using motor-generators or synchronous converters. A large percentage of all generating stations which have been installed recently—this includes many small stations as well as large ones—generate only alternating voltages.

309. Practically All Alternating-current Stations Generate Three-phase.—This refers to stations which have been in-

stalled recently. (There are still a number of two-phase stations and a very few single-phase stations in operation.) The reason for this is that three-phase generating and converting apparatus is the most economical and energy can be transmitted more economically with the three-phase system than with any of the others which are utilized directly. The three-phase can be readily transformed or converted into power of some one of the other systems if desirable.

NOTE.—Even if a large proportion of the output of a station must be transformed or converted to render it available for utilization, it is usually most economical to generate only one kind of energy. That is, for most cases in a station of any size, only three-phase alternating power should be generated. The reason why this plan is ordinarily followed is that with it the generating units can all be operated at greater loads. That is, the individual load factors of the generating units can be maintained at a maximum, due to the advantage that may thereby be taken of the diversity element. Furthermore, where only one kind of power is generated, the investment which must be tied up in reserve apparatus may be a minimum.

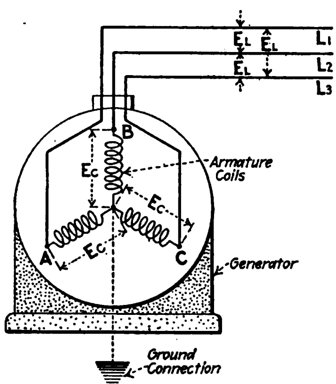


FIG. 237.—Diagrammatic representation of a star- or Y-connected, three-phase generator.

310. Three-phase Generators are Usually Star-connected (Fig. 237), because with this method of connection for a given voltage, E_L (Fig. 237) between line wires, the voltage E_C across each set of armature coils is less than it would be with a delta-connected generator impressing the same line voltage. In view of this, the number of turns in the star-connected generator coils is, for a given line voltage, smaller. Hence, conductors of a correspondingly larger diameter can be used for them than would be necessary with a delta-connected machine. Thus a more sturdy and satisfactory mechanical

* Much of the material which folllows is based on data contained in the article GENERATING STATIONS AND SOME FEATURES GOVERNING THEIR DESIGN by E. A. Lof of the General Electric Company, published in *Coal Age*, Feb. 6, 1915.

structure results. Furthermore, certain difficulties, due to local current circulating in the machine windings, which may occur with the delta are eliminated with the star connection.

311. Both Grounded and Ungrounded-neutral Systems are used. Which is preferable must be determined in each specific case after due consideration has been given to the factors involved. There are two reasons for grounding the neutral. One is to limit the voltage, between line and ground, which may be impressed on the insulators and apparatus.

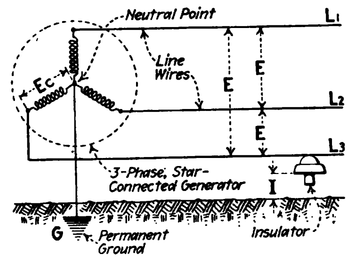


FIG. 238.—Accidental ground on a grounded-neutral system.

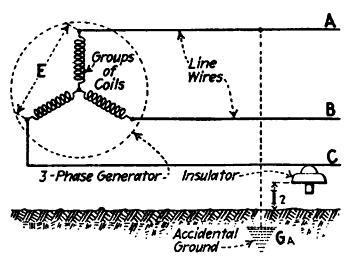


FIG. 239.—Accidental-ground on an ungrounded-neutral system.

EXPLANATION.—If a neutral is grounded, as at *G*, Fig. 238, it is evident that the electric stress imposed on the insulator at *I*, between line wire L_3 and ground, can never be greater than the voltage E_C which is 0.58 of the line voltage, *E*. If, however, the neutral is ungrounded as in Fig. 239, and an accidental ground, G_A, occurs, then the line voltage *E* is impressing on the insulator at I_2 between the line wire, *C*, and ground. The line voltage in a three-phase system always equals 1.73 times the voltage to neutral. (The voltage to neutral is shown by E_C in Fig. 237.)

The other reason for grounding a neutral is to insure that one of two or more sets of feeders will, by the action of the overload oil circuit-breaker inserted in it, promptly disconnect itself from the station if a ground occurs on that feeder.

EXPLANATION.—If an accidental ground, G_2 (Fig. 240), occurs on a feeder, F_1, supplied by a generator having a grounded neutral, a current will flow through the accidental ground as shown by the dotted arrows. This ground will be of sufficiently low resistance so that the current which flows will be of great enough intensity (amperage) to immediately operate the automatic oil switch or oil circuit-breaker, S_1. This will isolate F_1 from the system. If the neutral were not grounded the attendants in the station where the generator *G* was located might not be informed promptly of the existence of the accidental ground, G_2.

It follows that, if only one feeder extends from a station to a given load and that continuous service is essential, grounding is probably undesirable. If on the other hand, two or more feeders extend from the station to the same load then grounding may be desirable. As a rule it is good practice to omit the grounding of generators where only one or two feeders extend from the station unless the system operates at a very high voltage. Where the neutral is grounded merely to insure the automatic disconnection of a feeder in the event of a ground on it (Fig. 240), a resistance, R, may be inserted between the

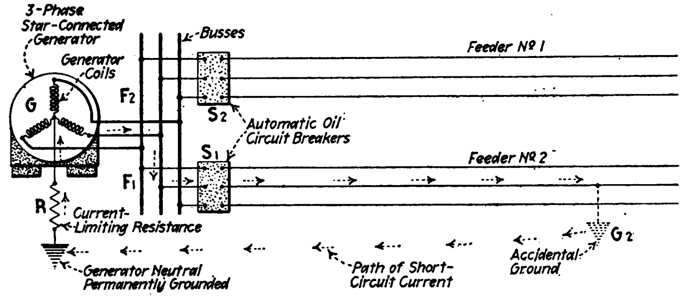


FIG. 240.—Showing how an accidentally-grounded feeder will disconnect itself from the generator on a grounded-neutral system.

neutral point of the generator and ground, to prevent the flow of excessive current in case of an accidental ground, G_2, on the line. Such a resistance should be so proportioned that it would permit enough current to flow to operate the automatic oil switches but would at the same time prevent the flow of a dangerously large current.

312. The Voltages for Alternating-current Generators vary with the conditions under which the plant operates. Occasionally where a very small plant serves only an incandescent-lighting load, the generator voltage is 110. More frequently a pressure of 220 is adopted for small plants which serve a three-wire system, the three-wire, 110-220-volt pressures (Fig. 241) being obtained with balance coils located at points near the load. Sometimes, in industrial plants where a considerable number of alternating-current motors are used, 480-

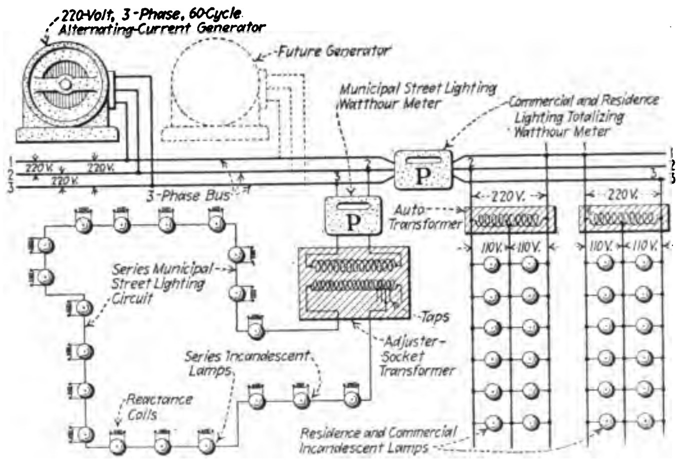


FIG. 241.—General scheme of generation and distribution for a town of about 1,000 inhabitants or less.

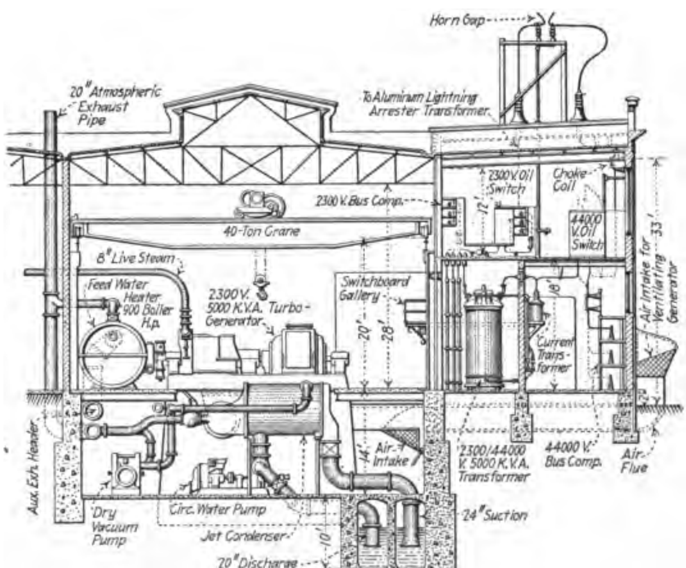


FIG. 242.—Arrangement of the generating and electrical equipment in a modern steam-turbine generating station.*

* E. A. Lof, in COAL AGE, Feb, 6, 1915.

volt three-phase generators are installed. Generators for 2,200 to 2,400 volts three-phase are very frequently used in towns and small cities for serving a general lighting and motor load. In large industrial plants three-phase 6,600-volt generators are ordinarily used. A pressure of 13,200 volts is the highest for which it is deemed desirable in the United States to wind alternating-current generators. Hence, a great many machines generate at this pressure. Where the transmission distance is sufficiently short it is economical to use 13,200 as

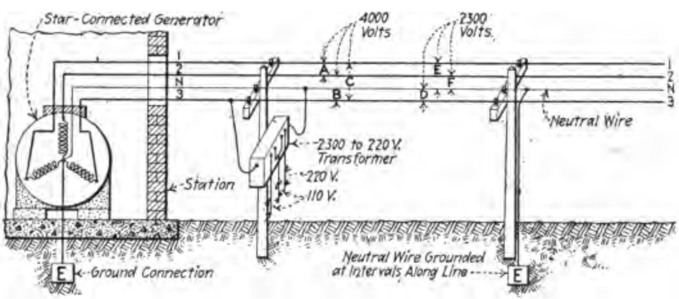


FIG. 243.—The four-wire, three-phase system.

the transmission voltage. In many plants the generation voltage is 2,300 or 2,400 (Fig. 242) and this pressure is raised with transformers to one suitable for the long-distance transmission. The four-wire, three-phase system (4,000 volts between line wires (Fig. 243) and 2,300 volts to neutral) is now being used extensively for local distribution for light and power in cities. In any case the generator voltage which should be selected is largely a matter of economics.

313. The Selection of the Capacities and Ratings of the Generators is a question which is always worthy of careful consideration. As a rule in modern installations each generator and its prime mover constitutes a complete unit. It is almost always the best practice to install two or more such units in every plant so that it will be possible, under all ordinary operating conditions, to work at least one of the units at its most efficient load; hence, in determining capacities and ratings, it is always desirable to base the determination upon

the graph of the load to be imposed on the station. It is, however, seldom possible to base the selection solely on the load graph because provision should be made for a certain growth in load. Also, the question of reserve capacity—that is, protection against accident and breakdown—should be considered.

314. The Rating of the Generator Should Be Proportioned to the Characteristics of the Prime Mover.—Both steam engine and waterwheel prime movers operate at maximum efficiency at certain definite loads. At loads greater or smaller than this maximum-efficiency load there will be a material decrease in efficiency. With internal-combustion engine prime movers of this type have no overload capacity) the point of greatest efficiency is the maximum load which the prime mover will pull. These elements should be given due consideration.

315. In Providing Reserve Capacity in generating equipment, that is, capacity which may be utilized in case of a breakdown of some of the generating apparatus, there are two expedients which may be adopted. That is, reserve capacity may be provided by: (1) *installing an extra unit or extra units which may be operated when one of the regular units is inoperative,* and (2) *the overload capacity of the regular units.*

NOTE.*—With the method of rating engine-driven units which is generally used which provides a liberal overload capacity for a few hours, the second expedient works out satisfactorily. For example, a plant of five units, each of which has an overload capacity of 25 per cent., can have one unit taken out of service when all of the units are operating at full-load without placing an excessive load on the remaining units. It is now the almost-standard practice of practically all steam-turbine manufacturers to rate their units on a maximum basis, that is, without any overload capacity. Under this method of rating it is necessary to utilize the first expedient noted above to provide reserve for emergencies. To maintain the reserve capacity at a minimum it may be desirable to have at least five or six units in the plant. With five units to carry the load and one reserve unit there is then only 17 per cent. of the installation held in reserve. If one reserve unit is considered inadequate the addition of another increases the reserve capacity to about 29 per cent. of the total.

* J. W. Shuster, TENDENCIES IN CENTRAL STATION PRACTICE, *Electrical Review*, Mar. 3, 1917.

Waterwheel and internal-combustion engine driven units have no overload capacity, hence in stations driven by prime movers of this type reserve capacity must be provided as outlined in expedient (2), above. That is, additional units must be provided for reserve.

316. Low Power Factor Decreases the Effective Capacity of a Generator so that if a station is to operate at a power factor other than 100 per cent. this should be recognized.

EXAMPLE.—If the power factor of a plant is 100 per cent. then for a 100-kva. generator, in such a plant, a prime mover capable of developing approximately 100 kw. output should be provided for the generator. However, if the power factor of the load which the plant serves is only 75 per cent., then to drive a 100-kva. generator a prime mover of only approximately 75 kw. output is necessary. If a 100-kw. prime mover were used approximately 25 per cent. or one-fourth of its capacity would be unavailable. Furthermore, the prime mover, instead of being fully loaded, that is, operating at high efficiency when the generator was fully loaded, would be operating at only three-fourths load with correspondingly low efficiency. (In the preceding example a generator efficiency of 100 per cent. has been assumed.) Actually the efficiency of a generator is always less than 100 per cent., but the principle involved is evident from the above even if the generator efficiency is not considered.

317. The Unit Principle Should be Utilized wherever possible. That is, all of the units in the plant should, insofar as feasible, be duplicates. The different essential elements of the installation, such as generating elements (comprising generator prime mover and its auxiliary apparatus) transformers, boilers, etc., should be arranged in groups or composite units. Each one of these groups should, in essence, be a complete central-station installation in itself. Then, if this plan is followed, a breakdown in some component piece of apparatus should effect only the group of which that component forms a part. The other groups should be capable of uninterrupted operation.

318. The Factors Which Should Determine the Location of the Apparatus in a generating station are: (1) simplicity, (2) reliability of operation and (3) extensions. Upon study it will be evident that, in general, the unit system of arrangement described in the preceding article satisfies all of these

requirements more completely than would any other arrangement.

319. In Locating the Prime Movers and Generators they should ordinarily be arranged on the main floor of the station. There should always be at least sufficient distance between units to admit a free passage around them and so that repairs can be effected without any unnecessary waste of time. In steam plants the condensers are usually located in the basement and the principal piping (Fig. 242) carried below the main floor.

320. The Exciters* should have a capacity sufficient for all of the synchronous apparatus in the station when all of the synchronous machines are operating at their maximum loads and at the operating power factor. It is not sufficient to provide only enough exciter capacity for excitation for the machines when they are running at unity power factor. The excitation required for power factors lower than unity is considerably higher than that required at unity.

321. The System of Excitation which is now considered good practice and which affords maximum reliability is that in which all of the exciting current is obtained from a common source. This common source should comprise as few units as possible. One or two units are generally provided for normal excitation and a third is installed as a reserve. It is always good practice to have the regular exciter driven by prime movers such as steam engines or waterwheels, while the reserve unit is motor-driven.

NOTE.—Another system of excitation which is now being used frequently is to install (for driving the exciters) low-voltage generators each of which is driven by a non-condensing steam turbine or a waterwheel. The exciters are then motor-driven, energy therefor being obtained from the low-voltage generator. The steam from the turbines exhausts into the feed-water heaters. In addition to the exciters, all of the other auxiliaries, such as circulating pumps, etc., are motor-driven.

* E. A. Lof, of the General Electric Company, GENERATING STATIONS AND SOME FEATURES COVERING THEIR DESIGN" published in *Coal Age*, Feb. 5, 1915.

322. The Exciter Voltage is, for small and medium-sized plants, 125 volts. For large installations 250-volt excitation is more economical.

323. In Locating the Exciters in a station it is, in general, desirable to place them near the center of the generator room so that the excitation wiring will involve minimum cost.

NOTE.—Where one exciter is furnished for each generator it should be located as close as is feasible to its generator. Exciters direct-connected to their generators are often used.

324. Automatic Voltage Regulators are always installed in modern stations. These, by acting on the fields of the exciters, maintain the alternating-current voltage constant at the bus-bars regardless of changes (within reasonable limits) of load on station or of changes in prime-mover speed. Voltage regulators are usually located on or near the switchboard.

325. The Number and the Capacities of the Transformers should be determined by the characteristics of the station and the load which it serves. In stations transmitting at medium or low voltage it is usually considered best practice to install one bank of transformers for each generating unit following out the unit principle recommended above. However, where the transmission voltage is high, the transformer bank should form a unit with the transmission line, each of the transmission lines terminating in the station in one of these units. Where this arrangement is followed switching on the high-tension side of the transformers is unnecessary as all of the switching can then be effected on the low-tension side of the transformers. In locating the transformers in the station, they are usually placed (Figs. 242 and 244) on the main floor back of the generators. They are enclosed in suitable fireproof compartments. A track is installed along in front of the tier of compartments so that the transformers may, when necessary, be readily removed for repairs.

326. Either Single-phase or Three-phase Transformers can be used. The modern tendency appears to be toward the utilization of three-phase transformers where the application of such is feasible.

NOTE.—The conditions under which single-phase transformers are preferable is where only one group is installed or where the expense of a spare transformer is unwarranted. In such installations the burning out of one phase of a three-phase unit involves considerable inconvenience since the transformer would have to be disconnected before repairs could be made. If single-phase transformers are used and connected in delta (on both primary and secondary) the damaged unit can be readily cut out and the other two operated at normal temperature—58 per cent. of the rated normal capacity of the group—until the damaged unit can be replaced.

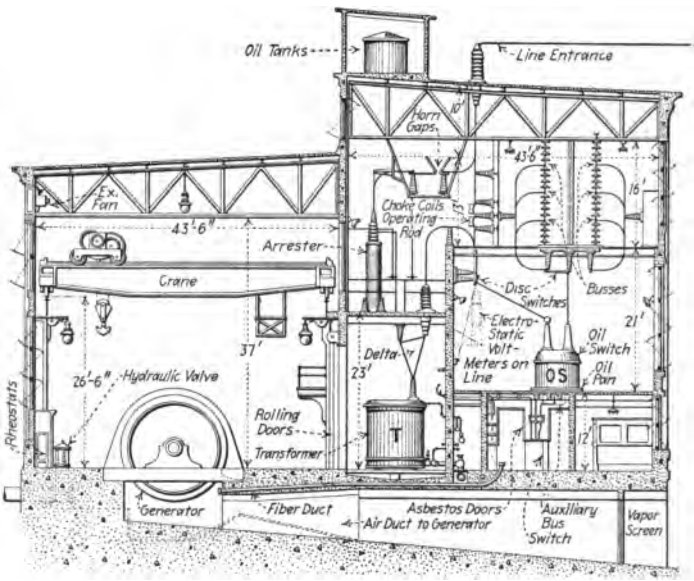


FIG. 244.—Sectional Elevation of a typical 110,000-volt Hydro-electric generating station.*

NOTE.—With the three-phase, shell-type transformers both the primary and secondary windings are delta-connected. Trouble in one phase will not prevent the use of the other two in open delta. By short-circuiting both the primary and secondary of the damaged phase and cutting it out of the circuit, the magnetic flux in that section is entirely neutralized. Three-phase transformers may be used in moderate-voltage installations having a large number of units. For high-voltage developments where each transformer bank should be of a capacity equal to that of the lines which it serves it is usually necessary to select single-phase transformers so as to obtain the required capacity and minimize the cost of the spare unit.

* E. A. Lof in COAL AGE, Feb. 6, 1915.

327. Transformers May Be Either of the Oil-cooled, Water-cooled or the Air-blast Type.—In the oil-cooled (Fig. 245) or self-cooled type the oil, heated by contact with the transformer core and windings, rises to the top in the transformer

FIG. 245.—Oil-cooled or self-cooling transformer. (This shows the tubular type.)

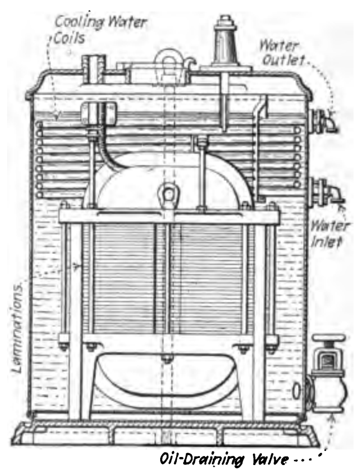


FIG. 246.—The water-cooled transformer.

case, from which the heat is radiated into the air. The tanks of self-cooling transformers are, therefore, usually made of corrugated sheet steel to provide maximum radiating surface. The self-cooled transformers are the most frequently used. Where water for cooling purposes is available, the water-cooled transformer (Fig. 246) is the most economical in first cost. In a transformer of this type, the oil circulates in a manner similar to that in a self-cooled unit. However, the greater

proportion of the heat is carried away by the water forced through a pipe coil which is submerged in the hottest oil in the top of the transformer. Ordinarily the water rate is approximately ½ gal. per min. per kw. loss, the temperature of the incoming water being 59 deg. F. In the air-blast transformer (Fig. 247), the cooling is effected by forcing a blast of

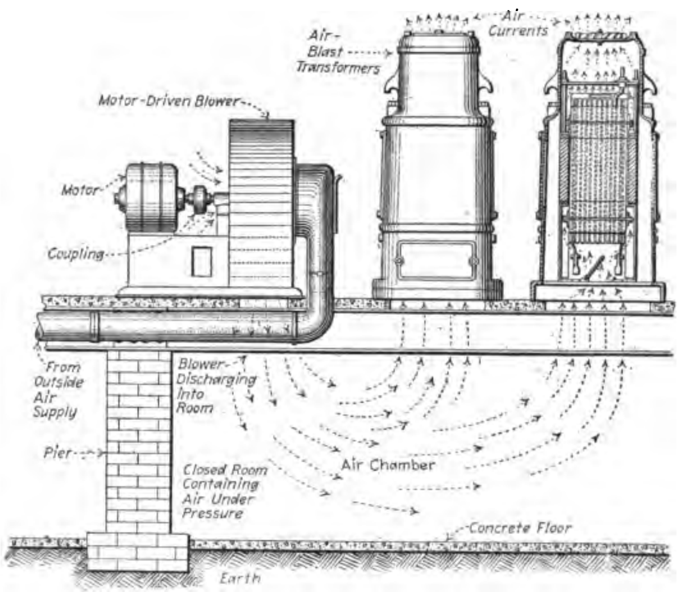


FIG. 247.—An air-blast-transformer installation.

air through ducts or spaces provided in the transformer structure. Transformers of this type are applicable for voltages up to about 33,000 but they are being rapidly superseded by those of the self-cooling type.

NOTE.—Circulating-oil-type transformers (Fig. 248) may be adopted where the only water available for cooling is hard or contains sediment. Such sediment might deposit on the insides of the coils of water-cooled transformer. But with the arrangement shown in the illustration, the deposit would be on the outside of the oil coils, hence readily removed.

328. External Reactances or Reactors* (Fig. 249) are now used in many stations of large capacity to limit the excessive current which would flow, if these reactors were not inserted, in

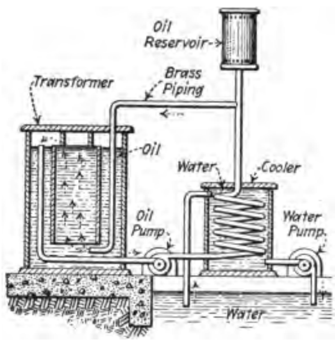


FIG. 248.—The circulating-oil-type transformer.

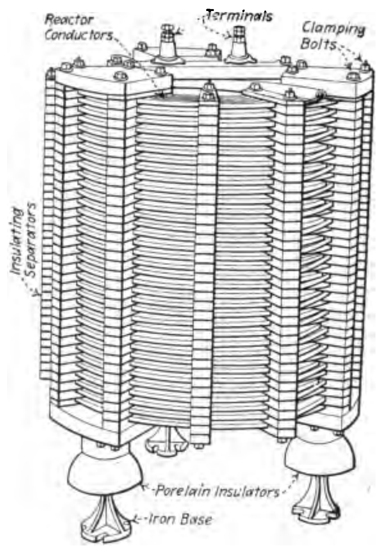


FIG. 249.—A current-limiting reactor.

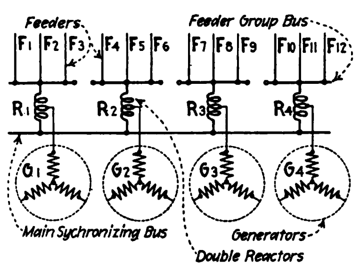


FIG. 250.—Single-line diagram of combined generator, bus and feeder-group reactance coil.

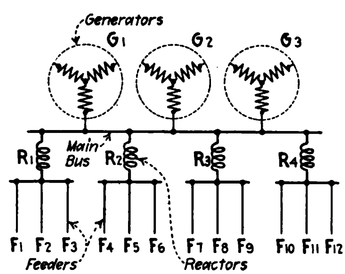


FIG. 251.—Single-line diagram showing reactors installed on feeder groups.

the case of a short-circuit on the system. It is not feasible to incorporate sufficient reactance in high-voltage turbo-gener-

* A. I. E. E. STANDARDIZATION RULES.

W. H. Dann and H. H. Rudd, THE USE OF CURRENT LIMITING REGULATORS, *Practical Engineer*, Aug. 15, 1915.

ators; hence, with generators of large capacity of this type, current-limiting reactances may be inserted in the generator lead or between the bus sections (Figs. 250, 251 and 252) or in the outgoing feeders.

329. The Percentage Reactance of a Reactor* is the ratio (expressed in per cent.) of the voltage drop across it, when full-load current flows at the voltage of the system.

EXAMPLE.—If the full-load current is 100 amp. (on a 10,000-volt, single-phase system or on a three-phase system with 10,000 volts to neutral) the drop across a coil having a reactance of 5 ohms will be: $100 \times 5 = 500$ *volts*. The percentage reactance of the coil will be: $100 \times 500 \div 10{,}000 = 5$ *per cent*. Or if the full-load current is 100 amp. on a three-

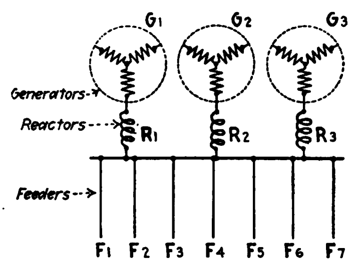


FIG. 252.—Reactors inserted in generator leads.

phase system, with 10,000 volts between phases, then the percentage reactance of the coil having a reactance of 5 ohms will be: $100 \times 500 \div (10{,}000 \times 0.577) = 8.66$ *per cent*.

The short-circuit current which will flow is: $100 \div$ (*the percentage reactance of the coil* + *the percentage reactance of the generator*) $\times$ *full-load current*. In the above case if the generator reactance is also 5 per cent., the short-circuit current will be $10 \times$ *full-load current*. On short-circuit the reactance will, in this case, have one-half the no-load voltage impressed across it.

330. The Location of the Switchboard and Switchgear should be determined by the capacity, voltage and general arrangement of the plant. In low-voltage, small-capacity plants where self-contained switchboards are used, all of the switchgear is mounted directly on or adjacent to the switchboard. The switchboard is installed in a convenient central

* *Electrical Journal*, Apr. 15, 1917.

location near one of the walls on the main floor of the station. Where the switchboard is of the remote-control type there are many different arrangements which may be used. It is usually considered desirable to so locate the control board that an unobstructed view of the station may be had from it. However, in certain very large installations the control board is in a room entirely separate from the generating room. The bus-bars and oil switches are located on the various floors of the switch house.* See Figs. 242 and 244.

* E. A. Lof.

SECTION 15

ADAPTABILITY OF STEAM, INTERNAL-COMBUSTION ENGINE AND HYDRAULIC PRIME MOVERS

331. The Type of Prime Mover Which Should Be Adopted for Any Specific Installation is, in general, a question of economics. Usually that prime mover is the best one

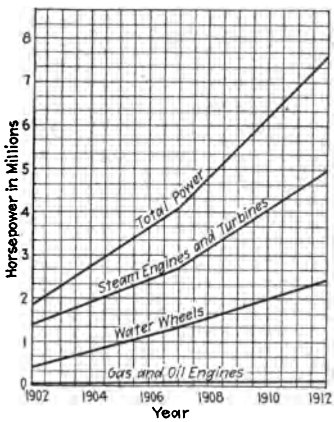


FIG. 253.—Prime movers used in central stations.*

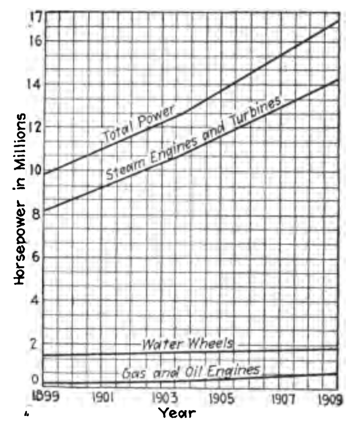


FIG. 254.—Prime movers used in the manufacturing industries.*

for a certain installation which will produce the energy in that installation at the least cost per kilowatt-hour. There are many elements which must be considered in such a determination of least cost. Some of these will be described briefly in the articles which follow. Figs. 253 and 254 show respectively the horse-power outputs of the prime movers used in central stations and industrial plants in the United States

332. The Application of Steam Prime Movers should, in the case of very small installations, be restricted to locations where

* E. A. Lof, *Coal Age*, Feb. 6, 1915.

coal is very cheap and where water power is not available. In medium-capacity installations, say those of from 300 to 5,000 kw., steam plants may be more economical than internal-combustion engine plants or those hydro-electric plants which require considerable capital expenditure for development. In large plants, where units of capacities of 5,000 kw. and upward may be utilized effectively, modern steam turbo-

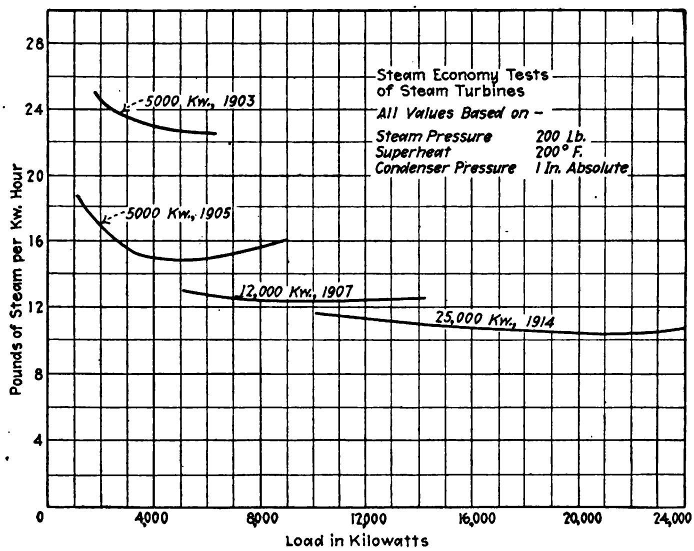


Fig. 255.—Graphs illustrating the development in the economy of turbo generators.*

generator energy generation will ordinarily prove much more economical than generation with an internal-combustion engine. It will also prove more economical than hydro-electric generation and transmission unless the investment required to develop the hydro-electric properties is unusually small.

Note.†—"The progress of the steam turbine (Fig. 255) has been so great that it has practically displaced the gas engine. As the cost of the gas-engine unit is probably seven or eight times as great as that of the turbine, the gas engine has been practically put out of the running insofar

* Copyright by Samuel Insull.
† H. G. Stott, Report of Efficiency Test on 30,000 kw. Cross-Compound Steam Turbine, read before the 1916 annual meeting of the A. S. M. E.

as large power-plant work is concerned." "Another interesting side light in this matter is the value of the turbine as the general prime mover in competition with anything else that could be cited. Fifteen years ago hydro-electric power developments were looked on as a choice investment worth lots of money with almost any cost of development. Water powers were developed that cost $200, $250 and $300 per kw.

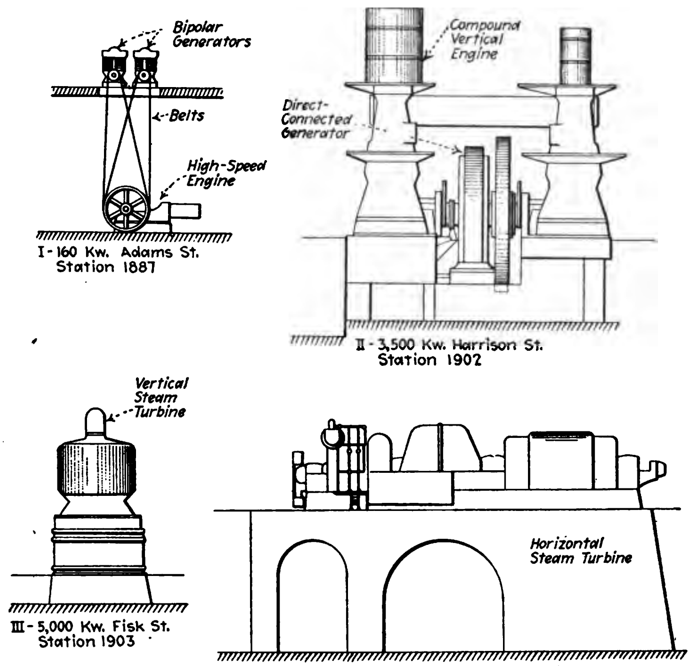


FIG. 256.—Four types of generating apparatus which have been use by the Commonwealth Edison Company of Chicago.*

Today you could not get money for an investment of that kind. The steam turbine has risen so high in efficiency and economy and decreased so much in first cost that it has driven out all possibility of developing many of these water powers. When you allow for the fixed charges, the steam turbine can make power more cheaply than the high-priced hydro-electric development." "Consider the case of Niagara Falls where there are no dams required and where there is practically an unlimited supply of power. The steam-turbine plant can compete with Niagara power today as long as the load factor of the Falls power is less than 50 per cent.

* Copyright by Samuel Insull.

The only chance for a financially successful water-power development is on the basis of a high load factor."

333. The Advantages of Large Turbo-generators are these: It is possible to obtain as much as six times the output capacity in the same floor space, Fig. 256. The first cost per kilowatt with the large turbo units is something like a fifth of the cost of equivalent reciprocating engine units. Furthermore, the water rates, that is, the steam consumptions of the large turbines, are in the neighborhood of one-half of the equivalent consumptions of reciprocating engine units.

334. Internal-combustion Engine Prime Movers Are Effectively Used at the present state of the art only in plants of small and medium capacity unless the cost of coal or of an

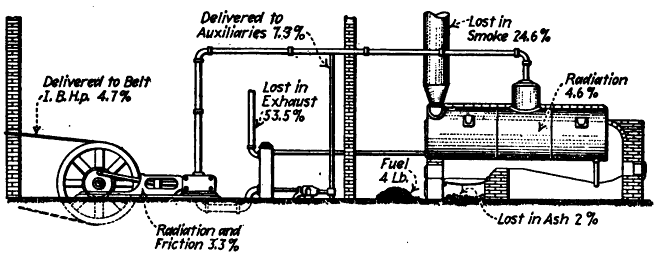


FIG. 257.—Losses in a non-condensing steam plant.*

hydro-electric development is unusually large. In small plants, say those up to 300 kw. in capacity, the internal-combustion engine prime movers may, unless the cost of coal is very low, be more economical than steam-engine plants. This is particularly true of small plants which operate only a portion of the 24 hr. For a small central-station plant which operates only at night or for a small industrial plant which operates only during the day, an oil or gas engine usually would generate power at minimum cost because such an engine does not involve the standby losses which obtain with the steam prime movers. As suggested in the above note, where a large power output is required, the internal-combustion engine has been put entirely out of the running by the

* R. H. Fernald, "PRODUCER GAS FROM LOW-GRADE FUELS," *Practical Engineer*, Dec. 15, 1914, p. 1200.

condensing steam turbine. If the cost of development is not excessive it may be possible to generate power with a waterwheel—hydraulic turbine—cheaper than with an internal-combustion engine. The producer-gas plants, which are much more economical than an ordinary non-condensing medium-capacity steam-engine plant (Figs. 257 and 258), cannot usually compete with the condensing turbo-generator outfit unless the cost of fuel which may be used in the producer is very low.

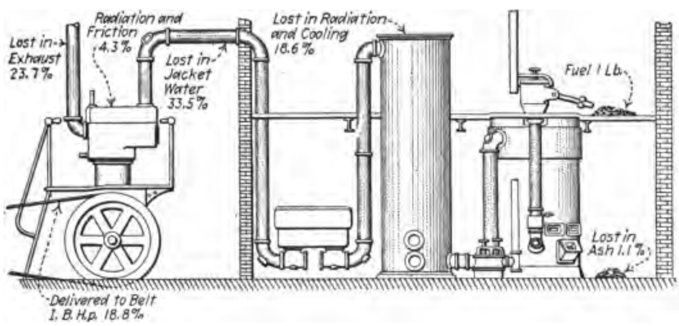


FIG. 258.—Loss in a suction gas-producer plant.*

335. Hydraulic Prime Movers Are Most Economical where the cost of developing the hydro-electric plant is not excessive. ~~the cost of developing the hydro-electric plant is not excessive.~~ It appears to be the common impression that merely because the water, which drives the turbines or waterwheel in a hydro-electric plant, costs nothing that the cost of the power developed should be correspondingly low. This is far from the truth, because in determining the total cost of the power developed it is necessary to include the fixed charges (interest, depreciation, insurance, taxes, and the like) on the investment required to develop the hydro-electric property. If it is necessary to pay these fixed charges on an expensive dam and on a large real-estate investment required for the storage-water area, and then in addition pay the fixed charges on a long, expensive transmission line, such fixed charges may

* R. H. FERNALD, "PRODUCER GAS FROM LOW-GRADE FUELS," *Practical Engineer*, Dec. 15, 1914, p. 1200.

more than overbalance the cost of the coal and attendance that would be required by a modern steam station. The fixed charges on the transmission line should, usually, properly be included with those on the hydro-electric plant and development. Without the transmission line the plant would be useless.

336. The Development of Low-head Hydro-electric Plants is likely to involve excessive cost. On the other hand, if, due to local conditions, it is possible to install a hydro-electric plant without incurring a large investment in dams, storage reservoirs and transmission lines, hydro-electric power may be developed very cheaply. Some of the high-head plants used in the West involve a relatively low first cost per kilowatt of capacity and, hence, can produce power very cheaply. Some hydro-electric plants for towns and factories are often economical where the plant can be located close to he load—so that a transmission-line investment is not required—particularly if an expensive dam and storage reservoir is not necessary.

SECTION 16

STEAM ELECTRICAL-ENERGY GENERATING STATIONS

337. Steam Plants May Be Conveniently Divided Into Four Classes.*—While there can be no definite dividing line, it is convenient to consider steam plants under four headings: (1) *small plants*, to include all of those under 300 kw. capacity; (2) *medium plants*, to include those between 3,000 and 5,000 kw. capacity; (3) *large plants*, those between 5,000 and 50,000 kw. capacity; and (4) *extra large plants*, which include those above 50,000 kw. capacity.

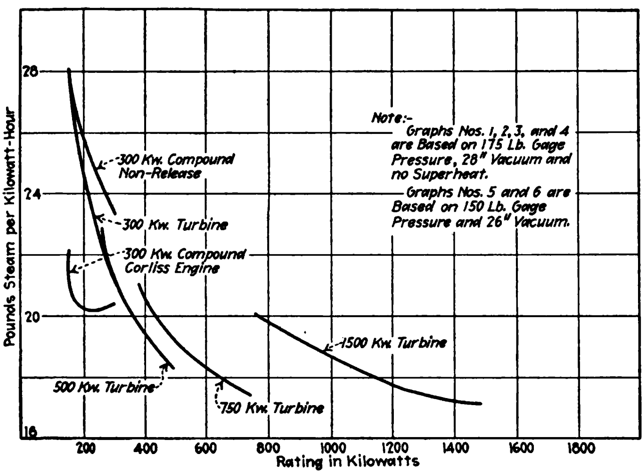


FIG. 259.—Graphs showing steam consumptions of relatively-small steam prime movers operating condensing.

338. In Small Steam Plants it is usually considered good practice to install only one or two units. Often only one unit of sufficient capacity to carry the entire load is used. The graph of Fig. 259 indicates the water rates of some relatively

* J. W. Shuster, TENDENCIES IN CENTRAL STATION PRACTICE, *Electrical Review*, Mar. 3, 1917.

small steam prime movers. It will be noted that the efficiency at full-load decreases rapidly as the size of the turbine decreases. It should also be noted that, with all of the units, the efficiency decreases rapidly as the load on the unit decreases. Hence, it is desirable to use the largest units possible and to always operate them at as nearly full-load as is feasible. Fre-

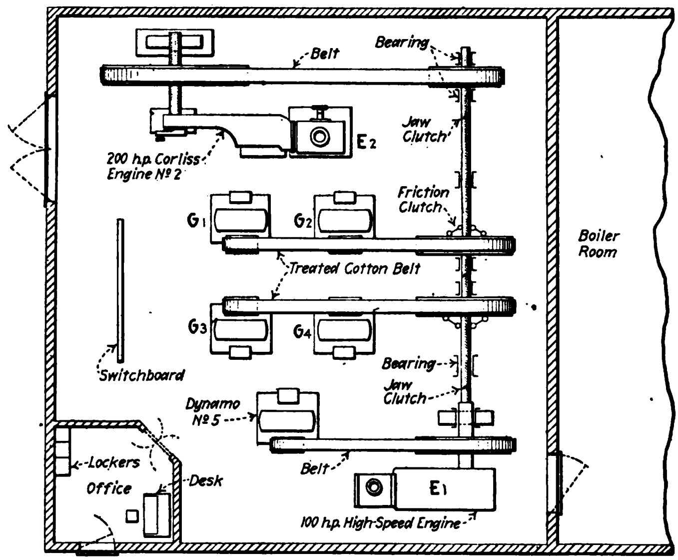


FIG. 260.—Lay-out for a small belted plant driven by a Corliss and a high-speed engine.

quently it is desirable, in these small plants, to operate non-condensing because the fixed and operating charges on the condensing equipment may be such that its first cost is not justified. In such installations where simplicity and reliability of service are the most important factors, a high-speed engine of the slide valve or non-releasing Corliss valve type may be used. Or instead Corliss engines may be installed. Non-condensing reciprocating steam engines are more economical than non-condensing turbines.

339. In Considering Belted vs. Direct-connected Steam-engine Units for Small Plants it should be recognized that the cost of the belted outfit is always lower than that of the direct-

connected, because where the generator is belted it may operate at high speed—which involves low generator cost. If the generator is direct-connected to the engine its speed must be the same as that of the engine, which is relatively low. Fig.

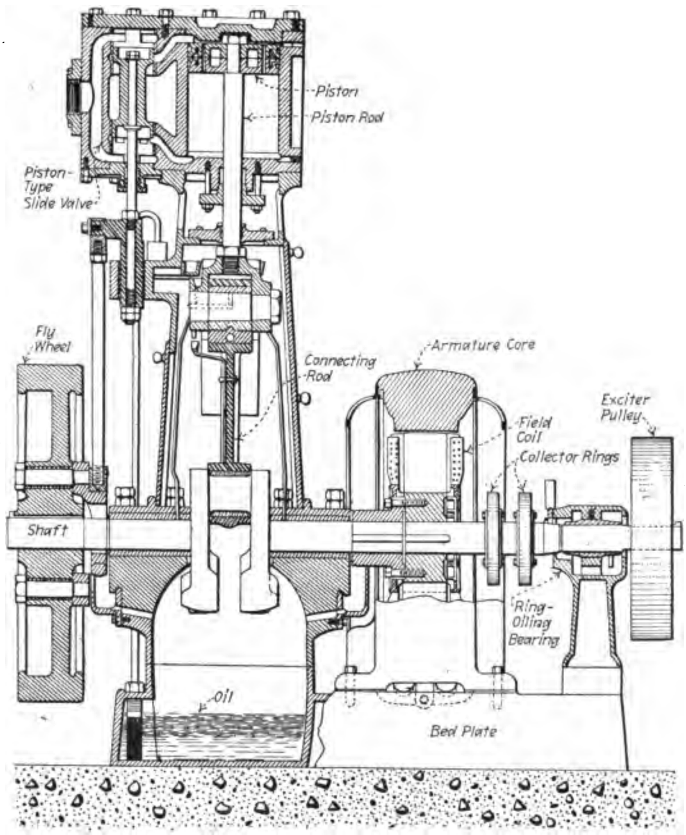


FIG. 261.—Direct-connected generating unit. A high-speed piston-valve engine driving a small alternator.

260 shows a typical belted installation.* A high-speed engine, E_1, is direct-connected to the jack shaft from which the generators are belted. A Corliss engine is also belted to the jack shaft. Both of the engines are used to pull the station at

* F. W. Salmon, *Practical Engineer*, June 15, 1915.

times of peak load. At other times either the Corliss engine, E_2, or the high-speed engine, E_1, were used to pull the load, depending upon which could operate most economically. Small stations of this general character may give satisfactory service in towns where the cost of coal is low and where reliability and ease of operation are of more importance than high economy.

340. A Small Direct-connected Generating Unit, similar to that of Fig. 261, may be used where economy of space is an important factor. A unit of this type which is equipped with a small slide valve engine will not be as economical as one having an engine with an automatic cut-off valve gear.

341. Average Full-load Steam Consumptions of Reciprocating Steam Engines of Different Types*

Type of engine		Range of h.p.	Speed in r.p.m.	Steam pressure gage, lb. per sq. in.	Steam consumption per i.h.p.hr.
High-speed	Simple non-condensing	30–150	375–275	80–110	35–32
	Compound non-condensing	100–150	325–250	100–150	27–25
	Compound condensing	100–300	325–250	100–150	20–19
Medium-speed, four-valve, non-releasing gear	Simple non-condensing	75–175	225–200	100–125	29–26
	Compound non-condensing	100–300	210–180	110–150	23–21
	Compound condensing	100–300	210–180	110–150	18–16
Slow-speed, "Corliss" or other four-valve with releasing gear	Simple non-condensing	100–350	100–70	80–125	28–25
	Compound non-condensing	200 and up	100–65	110–175	22–20
	Compound condensing	250 and up	100–65	110–175	16–14

* George Shaad in 1910 STANDARD HANDBOOK, p. 675.

342. A Small Alternating-current Generator Belted to a High-speed Slide-valve Engine is shown in Fig. 262. Units of this character may be used in small stations where the cost of fuel is low and where an easily handled outfit of very low first cost is imperative.

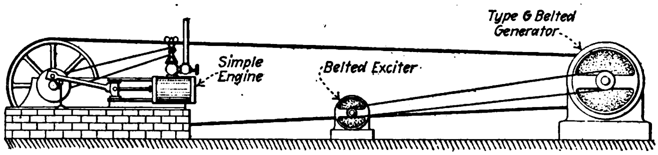


FIG. 262.—A high-speed simple engine belted to a small three-phase generator.

343. Uniflow Engines, which have been used in Europe for a considerable period but which have only recently been thor-

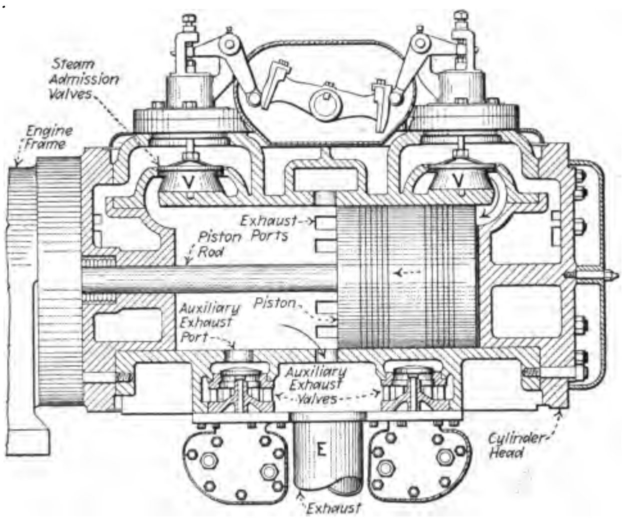


FIG. 263.—Sectional elevation through the cylinder of a Skinner-poppet-valve uniflow engine. (Full opening of exhaust through central ports.)

oughly developed in the United States, afford economical prime movers for small units. A uniflow engine is one in which the steam (Fig. 263) leaves the cylinder at its middle point, E. The steam enters the cylinder through valves, V, at either end and is discharged through ports in the middle

FIG. 264.—An 18" × 24", 200-r.p.m., Ames-Stumpf Uniflow engine operating condensing at 141 lb. pressure, superheat approx. 100 deg., driving an Allis-Chalmers 2500-kva., 220-volt, 3-phase, 60-cycle, generator served by a 125-volt exciter. (Ames. Iron Works, Oswego, N. Y.) This is installed in the plant of the Winsor (Vermont) Electric Light Company.

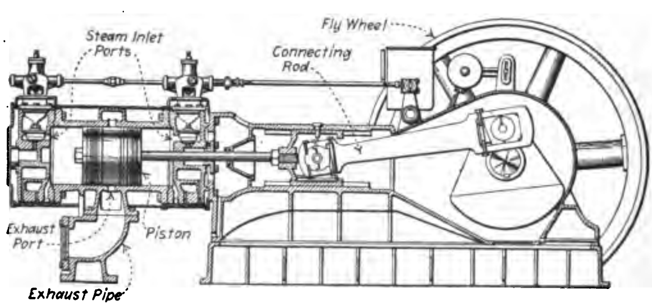


FIG. 265.—Sectional Elevation showing construction of the Ames-Stumph uniflow engine.

which are opened and closed by the cylinder piston, *P*, which acts as an exhaust valve. The economical performance of the uniflow engine is due to the fact that cylinder heads are always maintained at the same temperature so that there is little condensation in the cylinder. The steam always flows in one direction. With the simple engine, each cylinder head

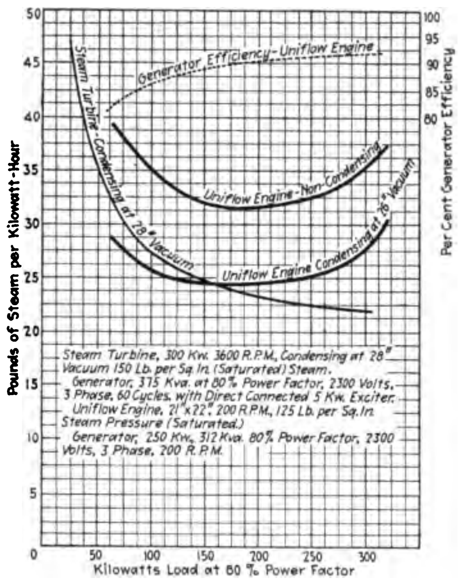


FIG. 266.—Characteristic performance graphs of the uniflow engine.*

alternately is heated and cooled as the steam is permitted to enter and exhaust from the cylinder. Uniflow engines can be used with superheated steam, which results in further economies. It appears that modern uniflow engines in capacities up to about 500 h.p. are as economical as any of the other types of steam prime movers. They can be obtained for both condensing or non-condensing service or for combined condensing and non-condensing operation. Fig. 264 shows a uniflow engine direct-connected to an alternating-current generator which is served by a belted exciter. Fig. 265 shows

* E. Hagenlocher; "CHARACTERISTICS OF UNIFLOW GENERATING UNITS," *Electrical World*, Feb. 10, 1917, p. 260.

the construction of an engine of the type reproduced in Fig. 264. Tests of uniflow engines operating non-condensing at 140 lb. boiler pressure have shown an economy of 30 lb. of

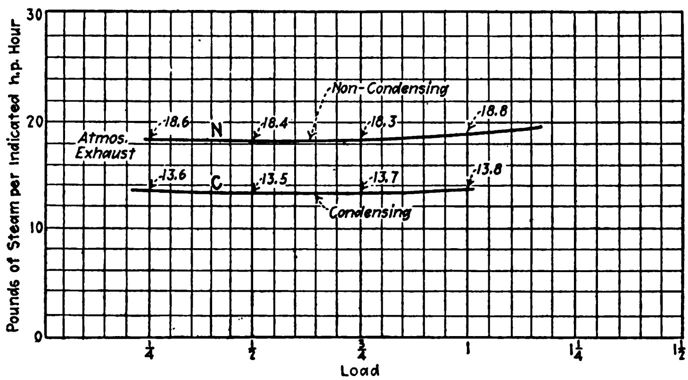


FIG. 266A.—Graphs showing water rates of a Skinner 21 in. × 22 in. uniflow engine running non-condensing and condensing, saturated steam at 140 lb. (This and the next illustration are from data on engines which were direct-connected to generators of 200 true kw. capacity and would be considered 320 h.p. engines at normal full load. However, the engines are good for 400 indicated h.p. for maximum continuous operation.)

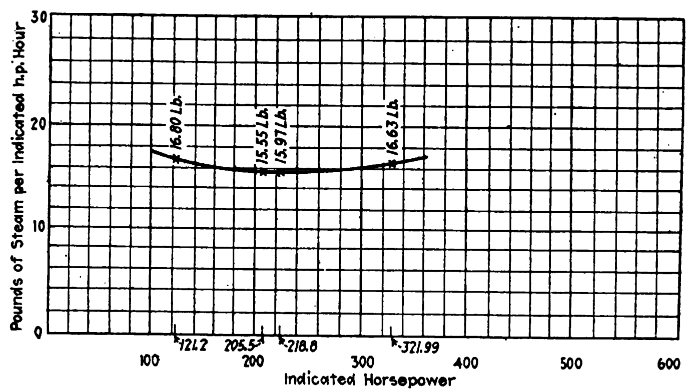


FIG. 266B.—Graph showing water rate of a 21 in. × 22 in. Skinner uniflow engine operating at a pressure of 149.1 lb. With a superheat of 102.5 deg. F.

steam per kw.-hr. when operating at full-load. Fig. 266 gives typical economy graphs for a uniflow unit as compared with a turbo-generator. It will be noted that the performance

graph of the uniflow engine near the full-load point is almost horizontal. That is, its efficiency does not change greatly with change in load, around the full-load point. This feature is shown in the performance graphs of Figs. 266A and 266B.

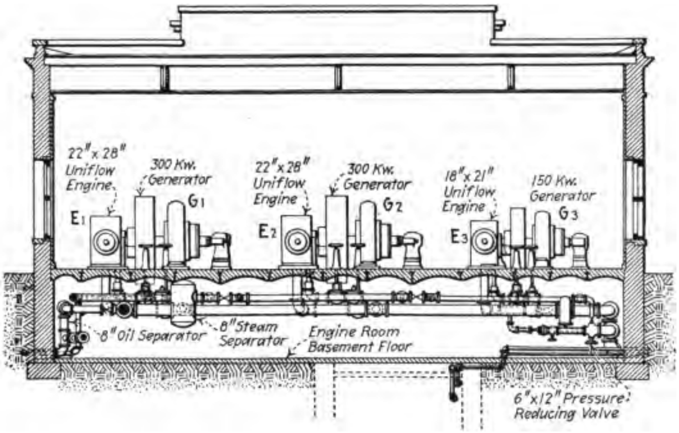


FIG. 267.—Sectional elevation through the engine room at the Springfield (Ill.) Capitol.

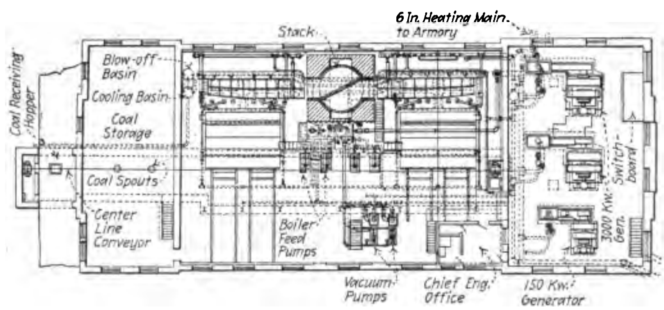


FIG. 268.—Plan of the uniflow engine plant and the boiler plant in the Springfield (Ill.) Capitol.

344. A Uniflow Engine Installation is shown in Figs. 267 and 268. These illustrate the equipment used for supplying electrical energy to the State buildings at Springfield, Illinois. Three direct-connected engine-driven units are installed. Each unit comprises a Chuse-Poppet valve engine direct-connected to a Westinghouse direct-current generator. One 18

by 21-in. engine drives a 200-r.p.m. 150-kw. 125-volt generator. Each of the other units is driven by a 22 by 28-in. engine, the generators being rated at 300 kw. and operated at 150 r.p.m. The 150-kw. unit is operated when the load is light—on Sundays and at night. The present day load is handled by one of the 300-kw. units.

345. Steam-turbine Stations have recently attained a position of great importance. This is particularly true of the stations wherein units of 20,000 kva. and greater capacities may be utilized. As suggested above, a modern, large, steam turbine generates power, under ordinary conditions, more economically than can a prime mover of any of the other types. Steam turbines are now widely used even in capacities of under 500 kw. They are also, because of their simplicity and reliability, used for driving the auxiliary apparatus in a station such as condenser pumps and feed pumps. High steam pressures are desirable, hence pressures ranging from 150 to 250 lb. are encountered. Since superheating also increases the economy, the steam is usually superheated from 125 to 150 deg. High vacuums ranging from 28 to 29 in. are employed.

EXAMPLE.*—A 500-kw. turbo unit, when operating on a steam pressure of 150 lb. and 125 deg. of superheat and a 28-in. vacuum has a steam consumption of approximately 17½ lb. per kw.-hr. A 15,000-kw. unit operating at a steam pressure of 250 lb. with 125 deg. of superheat and a 29-in. vacuum has a steam consumption of only 11½ lb. per kw.-hr.

346. Why the Large Steam Turbine Is so Economical may be explained thus: *First*, since no lubrication is necessary in the parts of the turbine with which the steam comes into contact, a higher degree of superheat is possible with it than with the reciprocating engine, for which cylinder lubrication is necessary. *Second*, when the turbine is used condensing, as it must be for maximum economy, the turbine utilizes the expansive power of the steam down to the highest vacuum which can be developed. The reciprocating engine can utilize the expansive power of the steam only down to possibly a 25- or 26-in. vacuum. If an endeavor is made with a reciprocating engine

* E. A. Lof.

to expand the pressure of a high vacuum, the low-pressure cylinders and the reciprocating parts associated therewith

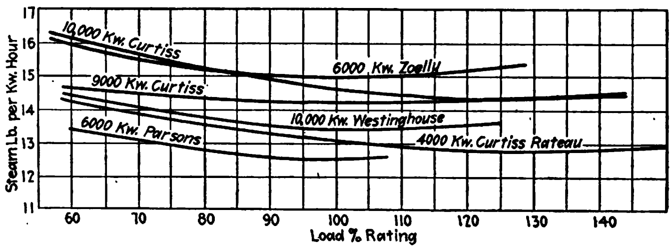


FIG. 269.—Water rate graphs of some medium-capacity condensing turbines.*

would be so large that their cost and frictional losses would more than offset the theoretical economies resulting therefrom. It is evident, therefore, from the foregoing, that a much greater part of the total energy in the system can be realized with the turbine than with the reciprocating engine. Another factor which renders the turbine so economical is its low first costs per unit of power output. This is because the turbine is inherently a high-speed prime mover.

347. The Efficiency Graph of the Turbine is almost flat Fig. 269. It follows that a turbine operates at good economy over a wide range of loads.

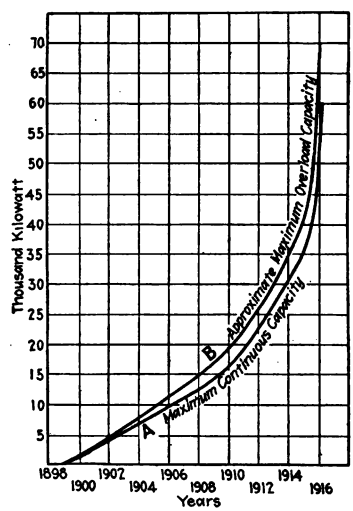


FIG. 270—Graphs showing how the capacities of steam-turbo-generator units have increased with the development of the art.

348. The Growth in the Capacities of Turbo-generator Units has been almost phenomenal. As suggested in the graph of Fig. 270, single units have been manufactured having outputs of

* Reginald J. S. Pigott, STANDARD HANDBOOK, July, 1915.

60,000 kw. The manufacturers assert that there is no reason why units of greater capacities than 60,000 kw. cannot be built provided there is a demand for them. Fig. 270 indicates the gradual increase in the capacities of the generating units in the stations of one central-station company.

349. A Comparison of the Steam Turbine and the Steam Engine as regards their applications is summarized in the following data* which relate particularly to units of less than 500 h.p.

NOTE.—*Applicability of Turbines.*—1. Direct-connected units, operating condensing. 60-cycle generators in all sizes, also 25-cycle generators above 1,000 kw. capacity. Direct-current generators in sizes up to 1,000 kw. capacity, including exciter units of all sizes. Centrifugal pumping machinery operating under substantially constant-head-and-quantity conditions and moderately high head, say from 100 ft. up, depending upon the size of the unit.

Fans and blowers for delivering air at pressures from 1½ in. water column to 30 lb. per sq. in.

2. Direct-connected units, operating non-condensing for all the above purposes, in those cases wherein steam economy is not the prime factor or where the exhaust steam can be completely utilized, and, in the latter case, particularly where oil-free exhaust steam is desirable or essential.

3. Geared units, operating straight condensing or non-condensing for all the above-mentioned applications, and in addition, many others which would otherwise fall in the category of the steam engine, on account of the relatively slow speed of the apparatus to be driven.

Applicability of Engines.—1. Non-condensing units, direct-connected or belted and used for driving:

(*a*) Electric generators of all classes excepting exciter sets of small capacity, unless belted from the main engine.

(*b*) Centrifugal pumping machinery, operating under variable head and quality conditions and at relatively low head, say up to 100 ft., depending on the capacity.

(*c*) Pumps and compressors for delivering water or gases in relatively small quantities and at relatively high pressures—in the case of pumps at pressures above 100 lb. per sq. in. and in the case of compressors at pressures from 1 lb. per sq. in. and above.

(*d*) Fans and blowers (including induced draft fans) for handling air in variable quantities and at relatively low pressures, say not over 5-in. water column.

* J. S. Barstow, TURBINES VS. ENGINES IN UNITS OF SMALL CAPACITIES, a paper read before the A. S. M. E.

(*e*) Line shafts of mills, where the driven apparatus is closely grouped and the load factor is good.

(*f*) All apparatus requiring reversal in direction of rotation, as in hoisting engines and engines for traction purposes.

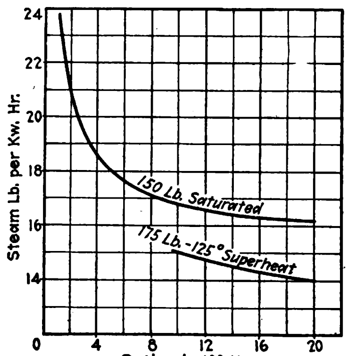


FIG. 271.—Steam consumptions of small turbines.

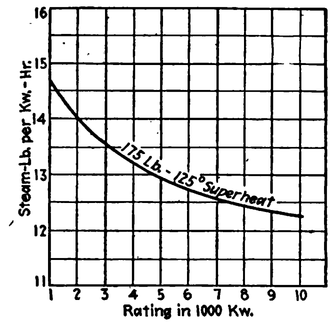


FIG. 272.—Steam consumptions of steam turbines of moderate capacities.

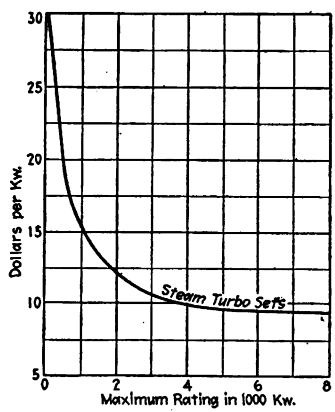


FIG. 273.—Approximate relative costs of turbo-generator units. (Cost of labor and materials are now fluctuating so widely that it is not feasible to give actual costs.)

2. Condensing units direct-connected or belted, for all the above purposes, particularly where the condensing water supply is limited, and where the water must be recooled and recirculated.

350. The Steam Consumptions of Small and Medium-Capacity Turbines* are indicated by the graphs of Figs. 271 and 272. The graph of Fig. 271 indicates the economics which may be effected through the use of a high steam pressure and superheat. Fig. 273 indicates the approximate cost of small and moderate capacity turbo-generator units.

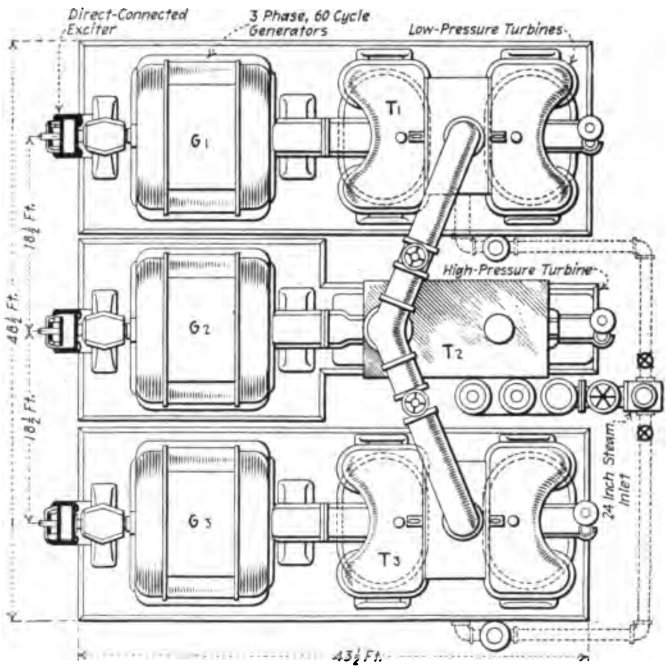


FIG. 274.—Three-cylinder, two-stage turbo-generator unit. Capacity is 60,000 kw.

351. The Cross-compound Principle As Used in Large Turbines is shown in Fig. 274 which illustrates the 60,000-kw. three-cylinder, two-stage unit purchased by the Interborough Rapid Transit Company of New York. Tests on this unit indicate at the point of maximum efficiency a water rate of 11.25 lb. per kw.-hr.

* David Elwell in a paper presented before a New England National Electric Light Association.

352. An Example of a Medium-capacity Turbo-generator Station is shown in Figs. 275 and 276, which illustrate a plant operated by the Arkansas Light and Power Company.*

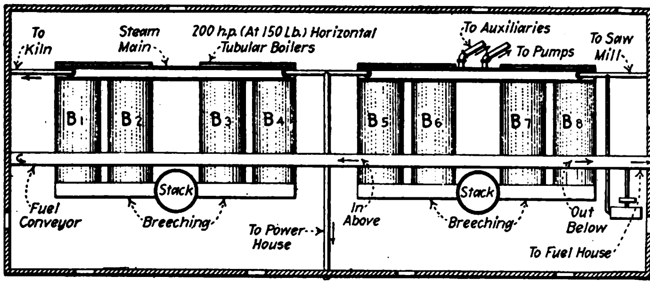


FIG. 275.—The boiler room in which the wood waste is burned.

In this installation wood waste from a saw mill and a planing mill is used for firing the boilers B_1 to B_8. The boiler house (Fig. 275) is located some distance away from the generating

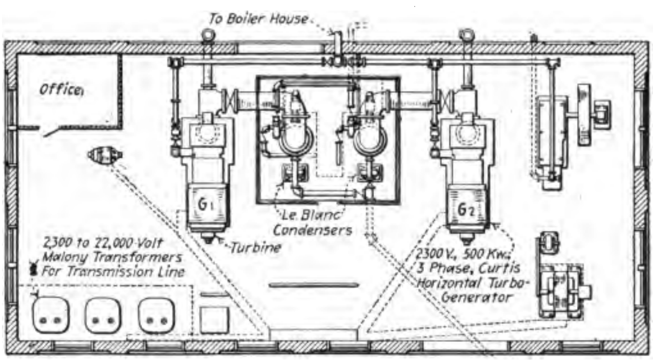


FIG. 276.—Turbo generator station utilizing steam generated with saw and planing mill waste.

station (Fig. 276), the boiler house being operated by a company which owns the saw and planing mills. This company sells steam to the Light and Power Company for the operation of the turbines G_1 and G_2.

* J. B. Woods, *Electrical World*, Apr. 14, 1917.

353. A Design for a Turbo Plant Having Only One Generating Unit is shown in Fig. 277. This plant is for the operation of a flour mill. A small 9 by 12 gas engine, *E*, installed in the engine room, is used for pulling the load at nights and at other times when it would be uneconomical to operate the turbine, *T*, at the small loads then existing.

354. An Example of a Large Turbo-generator Installation is shown in Figs. 278 and 279 which shows the Essex Station of the Public Service Corporation of New Jersey. This is said to be one of the most efficient steam stations ever constructed. The equipment comprises eight 1,373-h.p. boilers and the necessary superheaters and boiler-room auxiliaries. The generating equipment consists of two 25,000-kva. 13,200-volt General Electric Company turbo-generator units, *T*, in Fig. 278.

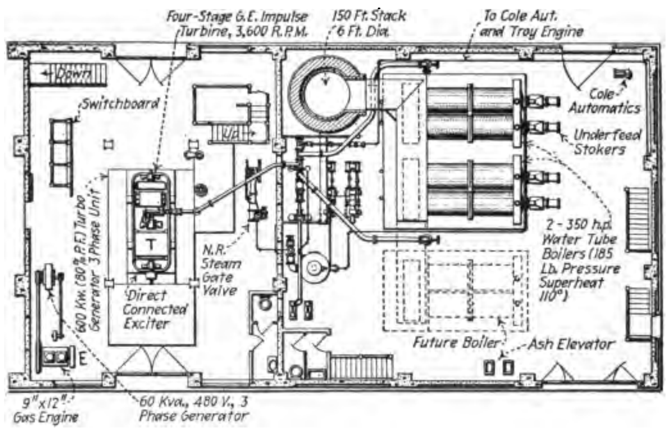


FIG. 277.—Plan view of the plant of the Commercial Milling Company.*

355. A Moderate-capacity Turbo-generator Plant is shown in Fig. 280, which illustrates the construction and general arrangement of the power plant of the Remington Arms and Ammunition Company at Bridgeport, Conn. The generating unit shown has a capacity of 2,000 kw.

356. Boilers for Steam-generating Stations are, in moderate

* *Power*, Dec. 22, 1914, p. 870.

and large-capacity plants, always of the water-tube type, inasmuch as this is the only type which will permit of the use of high steam pressures and the ready utilization of economizers and superheaters. While in some quarters the feeling exists

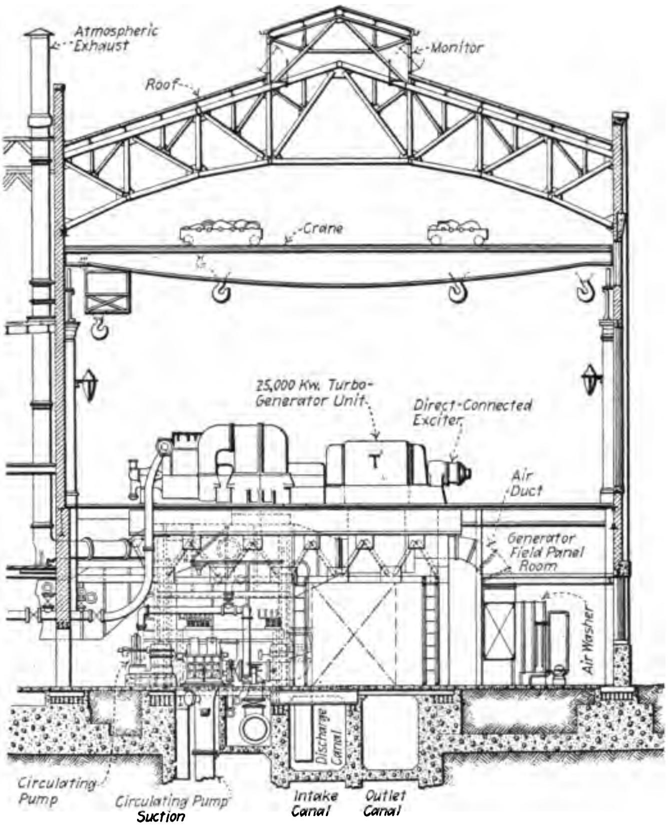


FIG. 278.—Sectional elevation of the turbine building of the Essex Station.

that 1,200 h.p. is as great a capacity as is desirable for one unit, boilers rated at 2,400 h.p. each have been used in certain installations. In medium-capacity plants, the capacity of each boiler unit is about 500 h.p. Fire-tube, that is return-tubular, boilers are now used only in the small non-condensing plants.

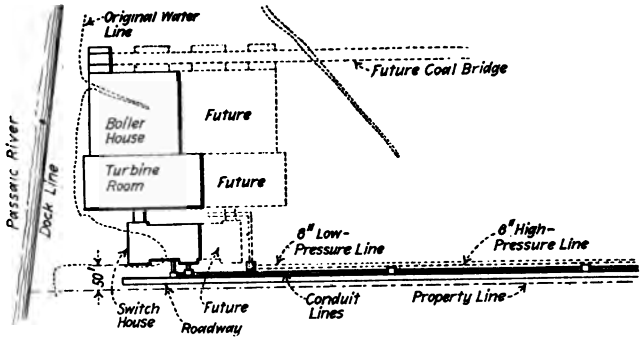


FIG. 279.—General lay-out of the Essex Station of the Public Service Corporation of New Jersey.

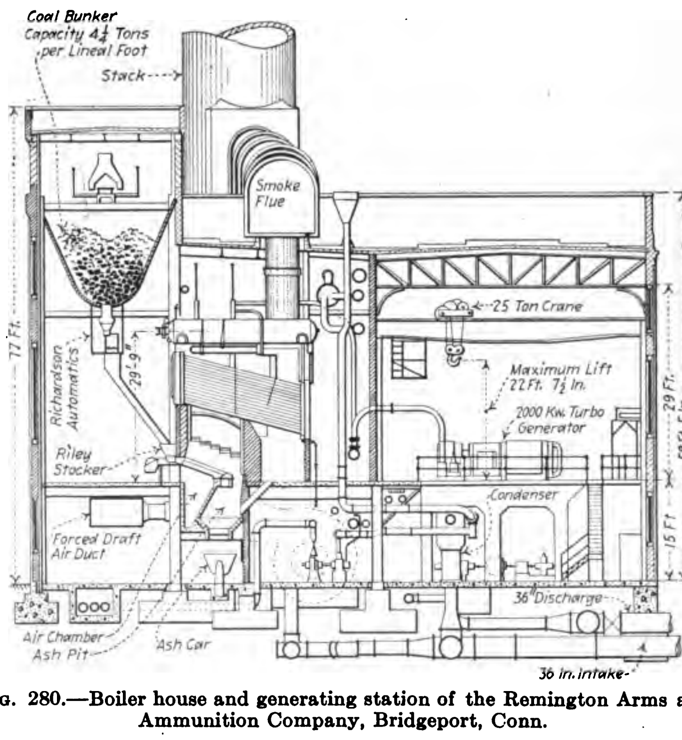


FIG. 280.—Boiler house and generating station of the Remington Arms and Ammunition Company, Bridgeport, Conn.

357. In Arranging the Boilers any one of several methods may be followed. The rows of boilers may be arranged facing an aisle running the short length of the station or they may be laid out in either single or double rows along a fire aisle. The illustrations show some of the different methods of boiler arrangement that have been utilized in practice.

SECTION 17

INTERNAL-COMBUSTION-ENGINE STATIONS

358. In Internal-combustion Engine Stations a prime mover may be either a gas engine, usually supplied with producer gas, or an oil engine. The producer-gas installations are suitable only for plants of medium or relatively large capacities and, as above suggested, a steam turbine is more economical in most installations of this character. The oil engines have been used to a considerable extent in medium-capacity plants in locations where the cost of oil is low. For very small plants which give service for a portion of the time, such as lighting plants operating in small towns only during the night, small oil engines are more economical than prime movers of any other type. Large gas engines have been used with great success in steel plants where by-product gas for every operation is obtained from the blast furnaces. Such installations are, however, of a specific character and can hardly be classed as central-station plants. Gas engines have been built for use in these plants in capacities of 4,000 to 6,000 h.p. output each.

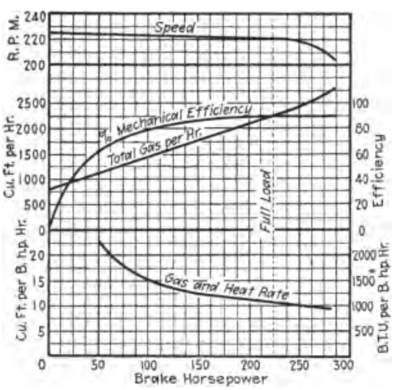


FIG. 281.—Typical internal-combustion-engine performance graphs. (This shows the performance of a 225-h.p. Westinghouse vertical gas engine.)

359. The Efficiency of an Internal-combustion Engine Increases With the Load (Fig. 281), so that the most efficient load for any internal-combustion engine is the greatest load which that engine will carry. It follows that internal-combustion engines should be, and are, rated on the maximum basis. That is, they are not rated with overload capacities

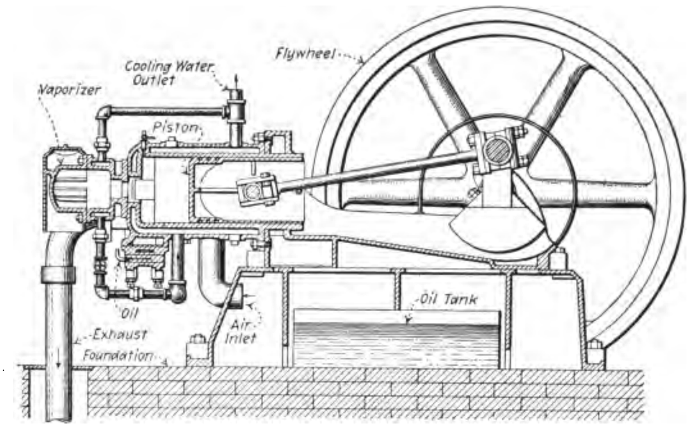


FIG. 282.—Section through a small low-pressure oil engine of the "hot-bulb" or "hot-ball" type.

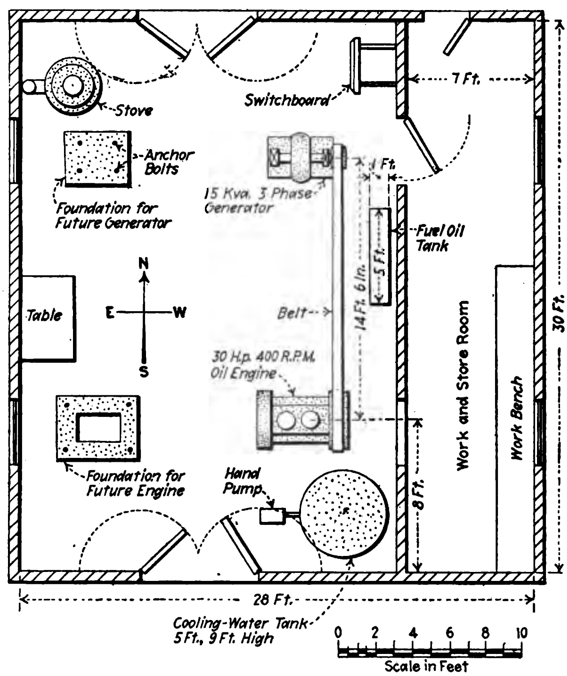


FIG. 283.—General lay-out of small oil-engine plant.

360. Oil Engines for Small-town Electric-lighting Plants are usually of the hot-bulb (Fig. 282) type. These can be operated on crude oil or kerosene. It has been found most economical in certain small plants to use kerosene rather than

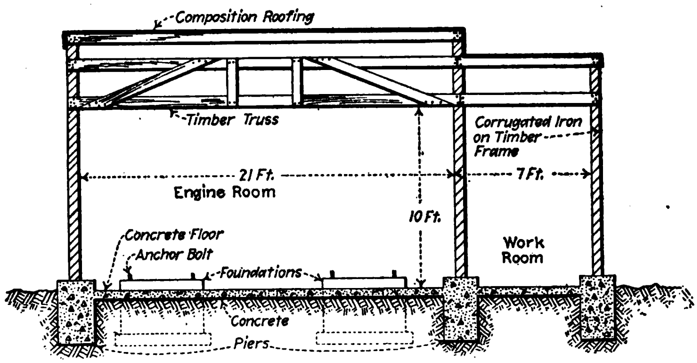


Fig. 284.—Transverse section of station.

crude oil because, in order to obtain a low rate per gallon, the crude oil must be purchased in tank-car quantities. In one of these small plants a considerable period elapses before a tank of oil can be consumed. Hence, the charges on a con-

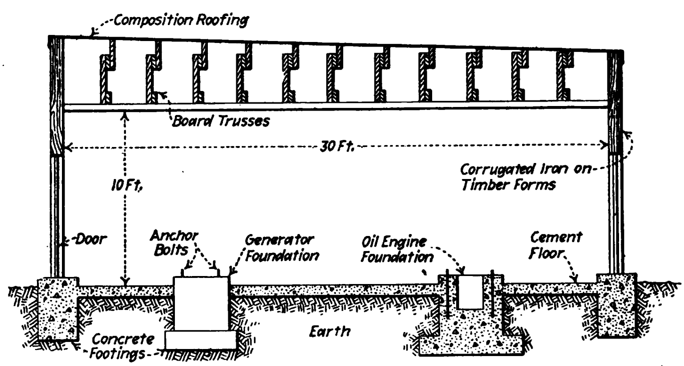


Fig. 285.—Longitudinal section of station.

tainer required to store the tank of oil, more than offsets the difference in cost between the crude oil and the kerosene. Kerosene can be obtained in practically any locality in relatively small drums.

361. The Lay-out of a Small Oil-engine Plant is shown in Fig. 283. A plant of this type might serve its consumers through a distribution system similar to that diagrammed in Fig. 241. The prime mover consists of a 30-h.p., 400-r.p.m. Remington oil engine which drives a 15-kva. belted generator. An economical construction for a building to house an equipment of this character is shown in Figs. 284 and 285.

SECTION 18

HYDRO-ELECTRIC STATIONS

362. Hydro-electric Stations May Be Divided Into Three General Classes: (*a*) *low-head stations,* 4 to 25 ft.; (*b*) *medium-head stations,* 25 to 300 ft.; and (*c*) *high-head stations,* 300 ft. to 3,000 ft. and up. Fig. 286 gives a graphic definition of the meaning of the word "head."

363. Waterwheels May Be Divided Into Three General Classes: (*a*) *Gravity,* (*b*) *reaction,* and (*c*) *impulse.* The characteristics of wheels of each type and illustrations thereof will be given below.

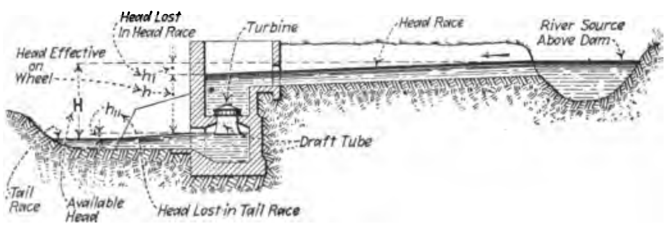


FIG. 286.—Graphic definition of the term "head."

364. A Gravity Wheel (Figs. 287 and 287A) is one which develops its power by virtue of the weight of the water falling through a distance equal to the head. The falling water carries with it as it goes down the buckets which catch it and thus develops power.

365. A Reaction Wheel (Figs. 288 and 289) is one which develops its power by virtue of the reactive pressure of the streams of water upon the movable buckets from which the streams are forced by the head of the water above.

366. An Impulse Wheel (Fig. 290) is one which develops its power by virtue of the force exerted by a stream of water which issues from a nozzle or guide and impinges on buckets

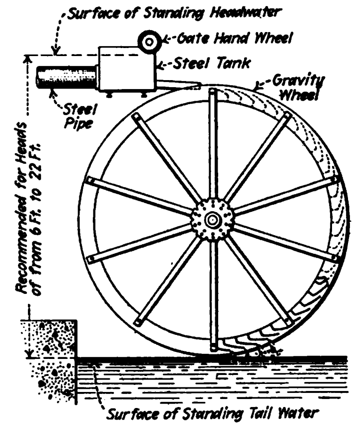


FIG. 287.—Gravity-type waterwheel, the most efficient wheel for very low, heads and small quantities of walts. (Manufactured by the Fitz Water Wheel Company, Hanover Pa.)

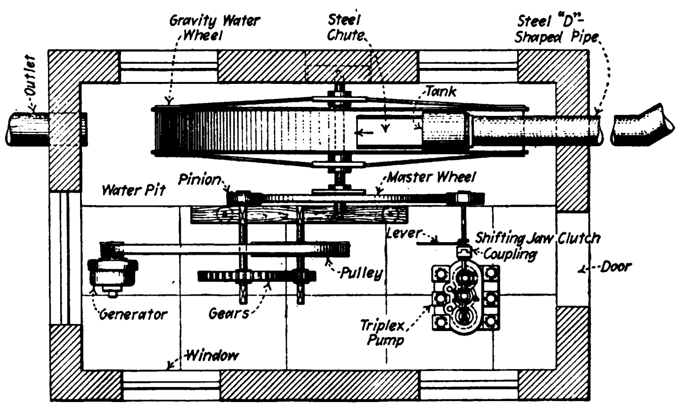


FIG. 287A.—A combination pumping and electric-light plant driven by a gravity waterwheel.

on the rotating wheel. The nozzles or guides are stationary and the wheel rotates.

NOTE that the gravity wheel develops its power solely by virtue of the weight of the falling water and that the reaction and impulse wheels develop their power by virtue of the potential energy due to the weight of the water which is first changed into kinetic energy.

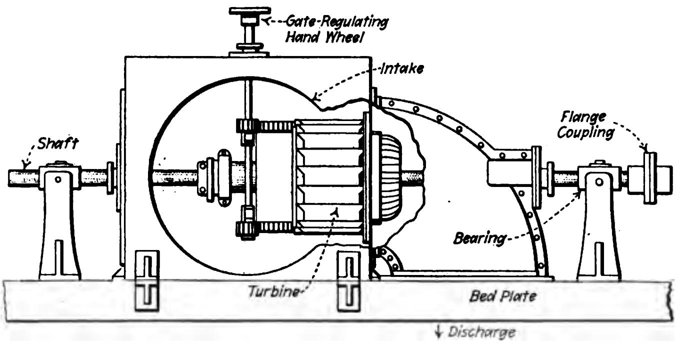


FIG. 288.—Illustrating the principle of the reaction wheel. (This shows a cylinder-gate, horizontal-type turbine mounted in a steel flume.)

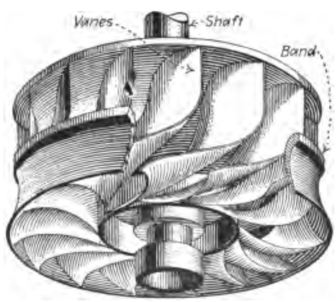


FIG. 289.—Runner of a mixed-flow turbine.

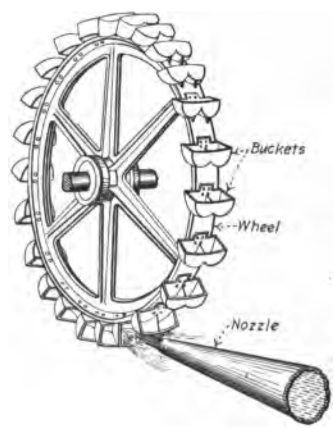


FIG. 290.—Impulse wheel and nozzle.

367. The Efficiency of a Waterwheel decreases both above and below the point of maximum efficiency, as shown in Fig. 291. This fact must be recognized in selecting the generator which is to be driven by a waterwheel unit.

368. The Applications for the Waterwheels of the Three Different Types May, in a general way, be given thus: Gravity wheels such as that illustrated in Fig. 287 are desirable only for very low heads and for the development of relatively small power outputs. They have been used successfully in certain very small central-station installations, in which the generator is belted to the wheel shaft. The reaction wheels are best adapted to relatively low heads and large quantities of water. In recent years reaction wheels have been used for all ranges

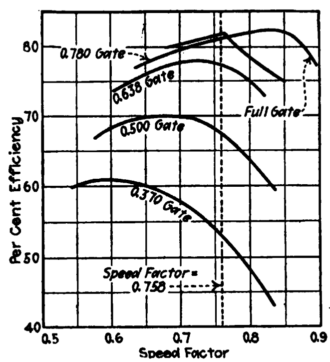


FIG. 291.—Efficiency graphs of a 48-in. turbine. (The wheel is designed to operate at a speed such that its peripheral velocity is 75.8 per cent. of the speed or velocity of the spouting water. The governor associated with it holds it constant at this speed. But it is obvious from the above that when operating at partial loads, at less than 0.78 gate, the efficiency decreases rapidly.)

of head from 600 to 700 ft. for large units. The impulse wheel is best adapted to high heads and small quantities of water. Thus, for heads greater than 200 ft. and of small flow of water, the impulse wheel is the most effective prime mover. The efficiencies of waterwheels may, for large units, be as great as 80 to 90 per cent.

369. The Names of the Elements of a Hydro-electric Installation are given graphically in Fig. 292. Obviously the typical arrangement shown in the illustration can not be followed in many instances. However, the nomenclature there given is of general application.

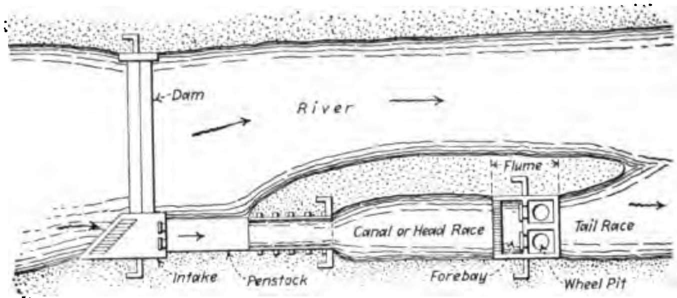


FIG. 292.—Illustrating the nomenclature of the essential elements of a hydro-electric development.

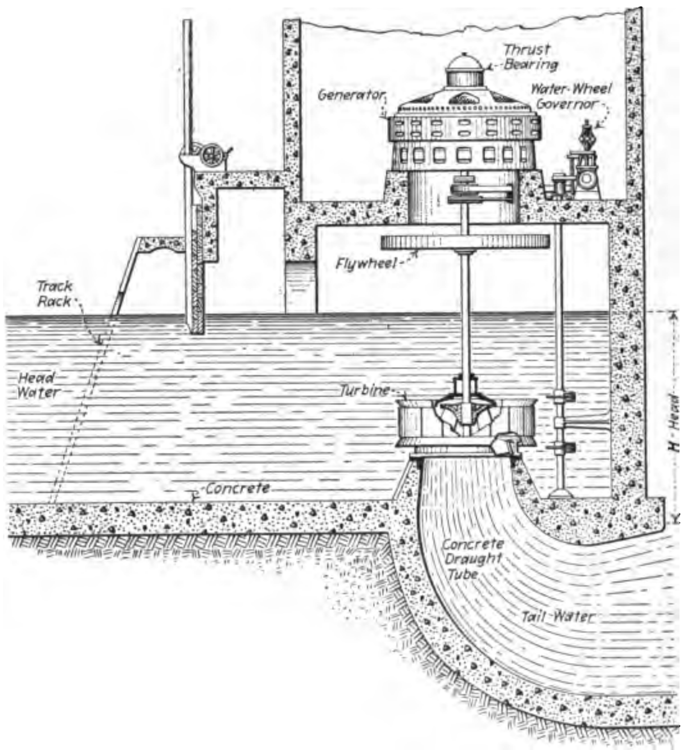


FIG. 293.—Low-head, vertical water wheel generator station. (Electrical Machinery Company.)

370. The General Tendency in Hydro-electric Station Design has been thus outlined by W. R. Thompson.* There is a tendency to do away with the clear spillway, hence, reservoir-level-controlling devices, either in the form of Tainter gates or automatic flashboards, are used. Frequently, the nearly constant reservoir level has many advantages such as minimizing the investment in reservoir land to that land which is ordinarily submerged. It insures the advantage of more uniform head on the plant and facilitates the handling of the ice which forms on the reservoir. This latter consideration is important on logging streams where logs are imbedded in the ice. The modern tendency, especially for low-head plants, is toward units consisting of the vertical, single-runner, large-capacity turbine (Fig. 293) with a direct-connected generator. Where a set of this type is used, economy in space results, and maximum reliability is insured, due to the accessibility of the wearing parts for inspection, adjustment, lubrication and repairs. The enclosed and heated forebay is now being used in Northern climates to prevent the interference by ice with operation. The continued use of a submerged forebay is justified because it eliminates practically all floating materials from the rack. Where conditions affecting the choice and size of units permits, there is a tendency to reduce the number of units in the plant to say three or four, rather than to have a large number of relatively small units.

371. The Typical Arrangement of a Low-head Hydro-electric Generating Equipment is shown in Fig. 293. This provides about as simple and effective arrangement as can be designed. The turbine and the generator are both of the vertical type and are direct-connected so that there is no unnecessary friction lost in gearing or belting. The weight of the waterwheel, the pressure of the downward water thrust and the weight of the revolving part of the alternator are carried by a thrust bearing located in the top of the generator. The guide bearings are self-aligning so that cramping can not occur. No step bearing is necessary or provided in the waterwheel.

* W. R. Thompson, TENDENCY IN CENTRAL STATION DESIGN, *Electrical Review*. Mar. 3, 1917.

372. A Low-head Hydro-electric Plant with a Horizontal Turbine is shown in Fig. 294. With this arrangement the generator is direct-connected to the turbine shaft and the water is impounded against one of the station walls. A modern low-head relatively large-capacity hydro-electric

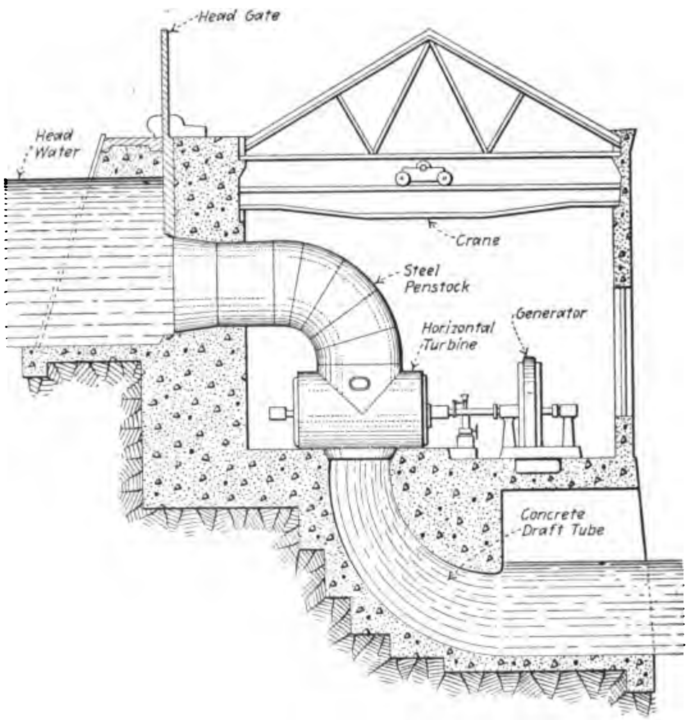


FIG. 294.—A low-head, horizontal-turbo-generator-unit installation. (James Leffel & Co.)

station is illustrated in Fig. 295. In this plant ten turbines each developing 10,800 h.p. on a 30-ft. head and operating at 53 r.p.m. are installed. The generators are 6,600-volt, three-phase, 60-cycle machines and are rated 10,000 kva.

373. A Typical High-head Hydro-electric Station is shown in Fig. 296. The impulse wheel is of the Pelton type. The

governing of impulse wheels is effected by deflecting the stream away from the buckets or by throttling it. Because of the high heads under which the impulse wheels usually operate, it is dangerous to attempt to govern by throttling alone, hence a system of governing which combines throttling and stream deflection has been adopted.

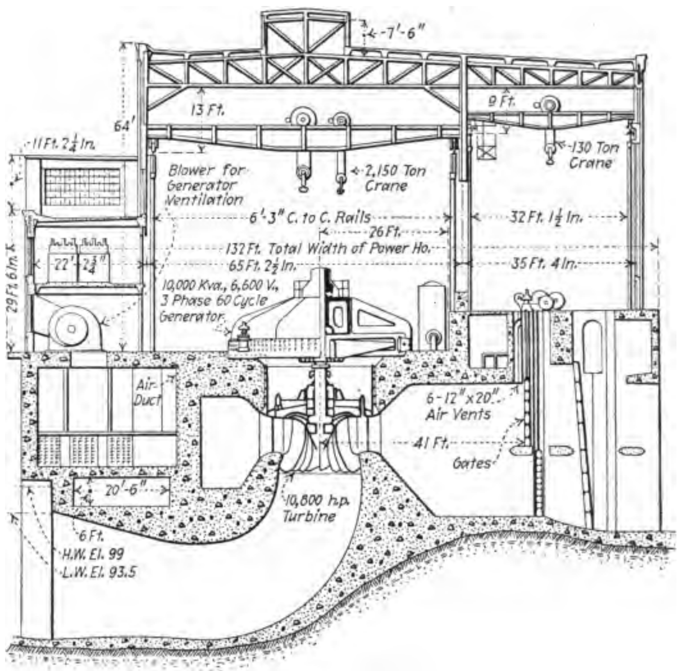


FIG. 295.—Hydro-electric station of the Cedar Rapids (Canada). Manufacturing and Power Company (*General Electric Review*).

374. The Largest Hydraulic Single-runner Turbine Ever Built is of 31,000-h.p. capacity (Fig. 297) and is to be installed at the aluminum plant on the Yadkin River in North Carolina. The head is 188 ft. The speed under an effective head of 188 ft. is 150 r.p.m. An efficiency exceeding 91 per cent. at full-load is expected. The generators are 13,200-volt machines rated at 18,000 kva. The turbines were built and installed by

the Allis-Chalmers Company and the generators and exciters by the General Electric. As shown in Fig. 298 the plant contains three of these 31,000 h.p. units. No transformers are required in the station, inasmuch as the energy is generated at 13,200 volts which is also the transmission voltage. Fig. 299 gives an idea of the complete development.

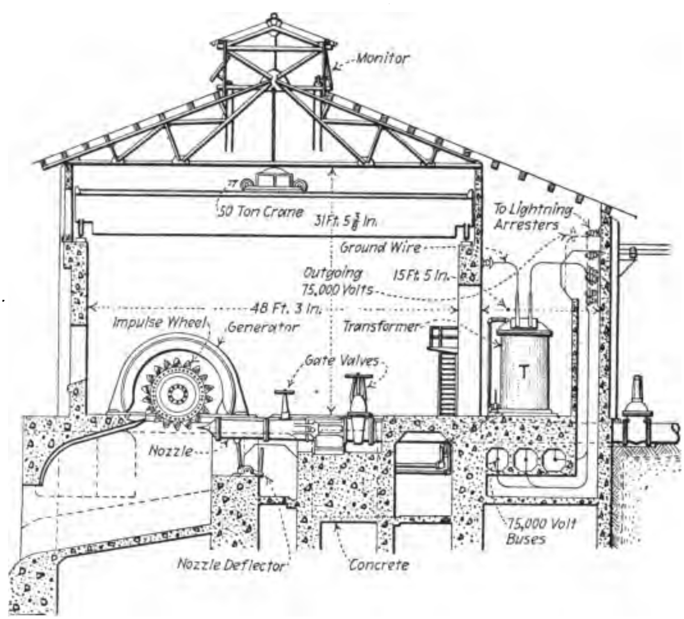


FIG. 296.—Sectional elevation of the Edison Electric Company's hydro-electric station at Kern River, California, containing four 10,750 h.p. Allis-Chalmers impulse wheels.

375. The Keokuk, Iowa, Hydro-electric Station is shown in Figs. 300, 301 and 302. The ultimate capacity of the station is 300,000 h.p. Energy is transmitted over a distance of approximately 200 miles in certain directions to St. Louis and other cities in Missouri and Iowa. The initial installation of turbines comprises fifteen units each having a normal rating of 10,000 h.p. based on a head of 32 ft. The generators have a maximum continuous rating of 9,000 kva. at 11,000 volts

and operating at 80 per cent. power factor. The normal speed is 55.7 r.p.m. This is a 25-cycle plant. For energy trans-

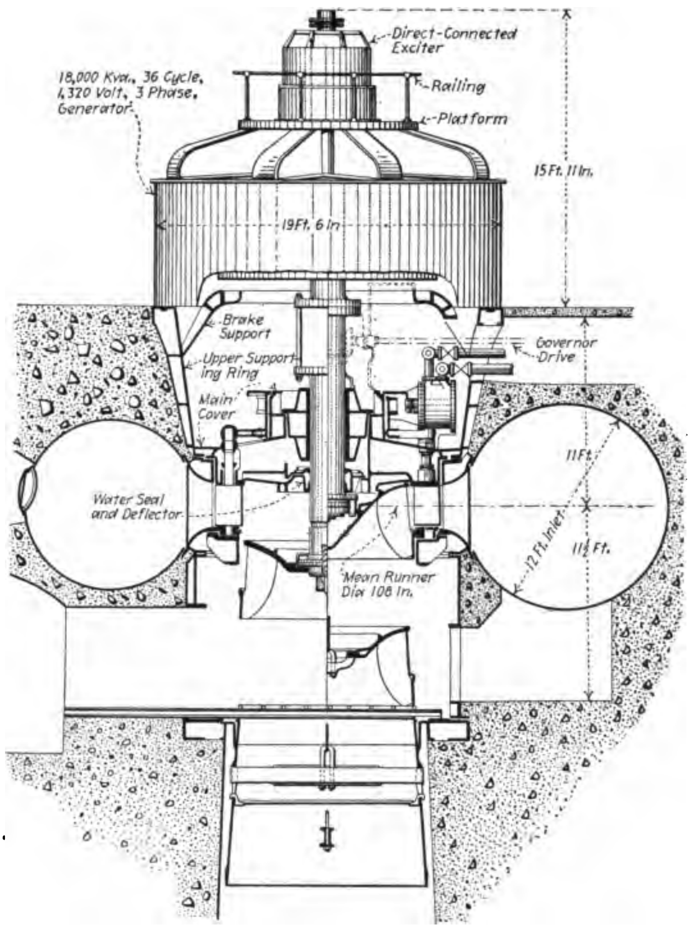


FIG. 297.—Sectional elevation of the 31,000 h.p. turbo generator units used in the Yadkin River development (in North Carolina) of the Tallassee Power Company. (The illustration shows the method used in dismantling the runner.)

mission to St. Louis the voltage is stepped up to 110,000. For shorter distances a voltage of 66,000 is used.

376. Outdoor Hydro-electric Plants* have been proposed. Figs. 303, 304, 305 and 306 show the general construction and arrangement. It is anticipated that material economies

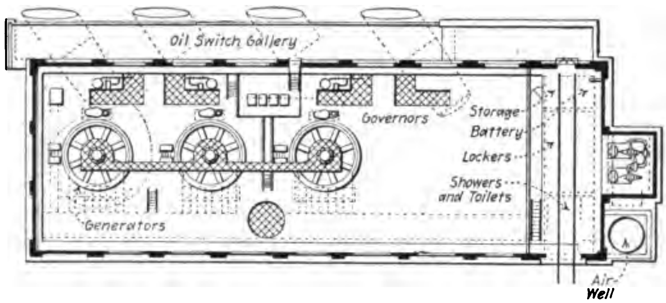


FIG. 298.—Plan view of the Yadkin-River hydro-electric station.

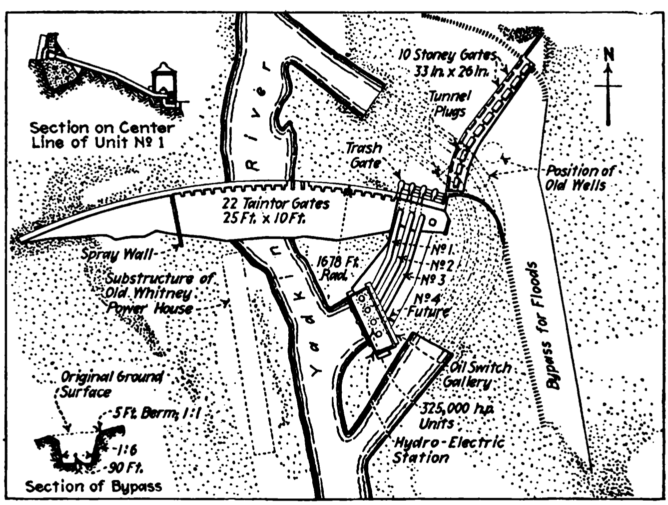


FIG. 299.—The Yadkin-River hydro-electric development.

will be realized through the omission of the building (which ordinarily houses the generating equipment) in a plant of this character. Outdoor switching and transforming stations

* *Electrical Review*, Sept. 25, 1915; p. 689.

have been in successful operation for a number of years, so there appears to be no reason why an outdoor hydro-electric

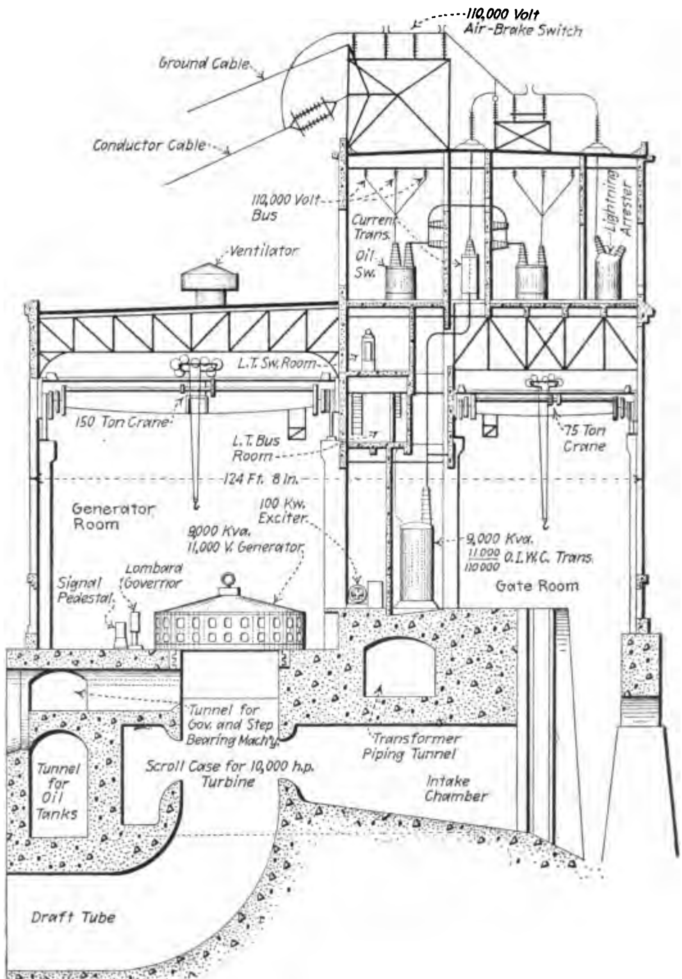


FIG. 300.—Sectional elevation of the Keokuk hydro-electric station.

plant should not also be successful. The plant illustrated was a tentative design proposed by R. J. McClellan, Chief

Engineer of the Electric Bond and Share Company. Climatic conditions and violent winds were the determining causes for eliminating the power-house superstructure. All

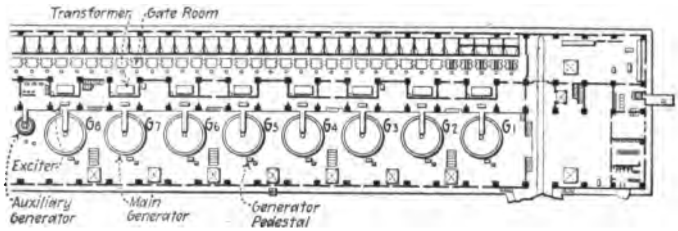


FIG. 301.—Plan view of half of the Keokuk hydro-electric station. (Compare this with the sectional elevation shown in another picture.)

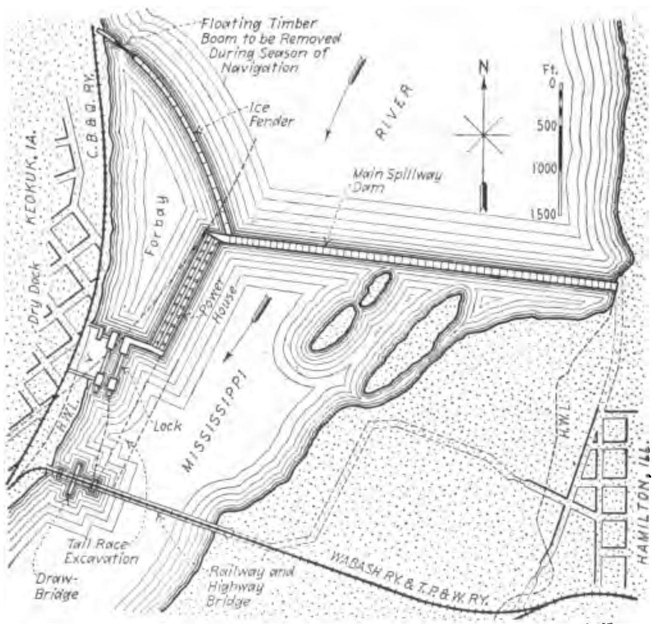


FIG. 302.—The Keokuk (Iowa) development of the Mississippi River Power Company.

of the generators and transformers are located outdoors. The control boards and exciters are installed in a structure over the tail-race where a repair shop also is located.

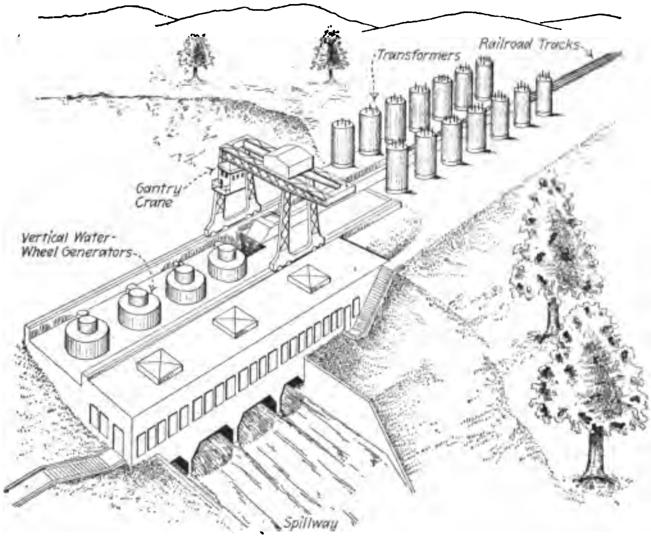


Fig. 303.—Showing general arrangement of the proposed outdoor hydro-electric station.

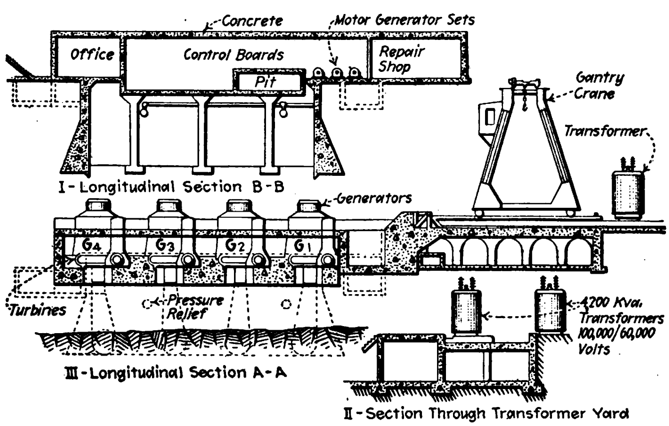


Fig. 304.—Showing various sections taken through the outdoor hydro-electric station.

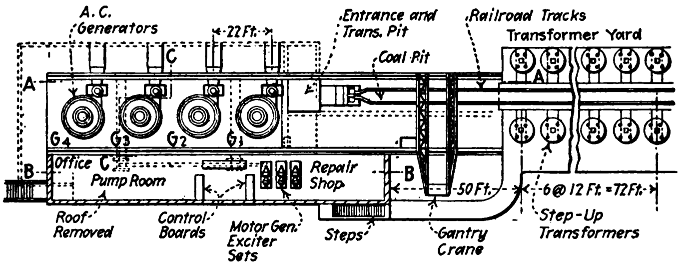


FIG. 305.—Plan view of proposed outdoor hydro-electric station.

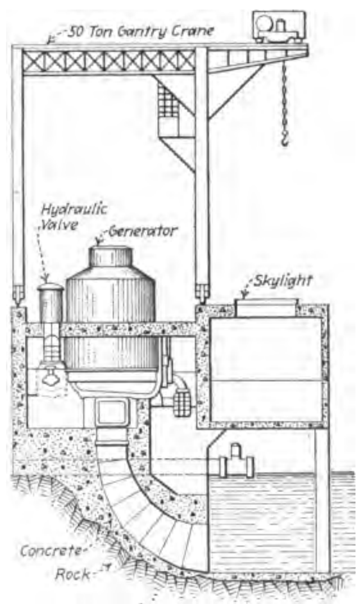


FIG. 306.—Section C-C. Through the generator platform.

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